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Application of Methods and Models for Prediction of Land Surface Erosion and Yield

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This document provides guidance on methods to estimate watershed sediment yield. It also reviews procedures for estimating the inflowing sediment load and gradation for use in sediment assessments or mobile boundary hydraulic and sedimentation studies. The focus is on development of data for HEC-6. HEC-6 is a numerical model that can be used for the prediction of sediment movement and deposition in rivers and reservoirs. References are provided throughout this document for sources of information and data. Readers are encouraged to check these sources. This document was prepared by Northwest Hydraulic Consultants, Incorporated. D. Michael Gee, Training Division, HEC, was the project manager and provided assistance in preparing this document. Josie Garcia-Moreno, Training Division, HEC, performed final edit and formatted document. Vern Bonner was Chief, Training Division, and Darryl Davis was the Director of HEC during the preparation of this report.

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CONVERSION FACTORS
NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

MULTIPLY	BY	TO OBTAIN
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	5/9*	degrees Celsius or Kelvin
feet	0.3048	meters
inches	2.54	centimeters
miles (US statute)	1.609347	kilometers
tons (2,000 pounds, mass)	907.1847	kilograms

* To obtain Celsius (C) temperature values from Fahrenheit (F) readings, use the following formula: C=(5/9)(F-32). To obtain Kelvin (K) readings, use: K=(5/9)(F-32)+273.15.

Preface

This document provides guidance on methods to estimate watershed sediment yield. It also reviews procedures for estimating the inflowing sediment load and gradation for use in sediment assessments or mobile boundary hydraulic and sedimentation studies. The focus is on development of data for HEC-6. HEC-6 is a numerical model that can be used for the prediction of sediment movement and deposition in rivers and reservoirs. References are provided throughout this document for sources of information and data. Readers are encouraged to check these sources.

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Chapter 1

Introduction

1.1 Scope and Objectives

This document presents methods for estimating sediment discharge and gradation from watersheds for conducting sediment assessments or mobile boundary hydraulic and sedimentation studies. Following an introduction in Chapter 1, Chapter 2 presents a brief summary discussion of key geomorphic processes affecting watershed sediment production and yield. Chapter 3 briefly summarizes several methods for estimating sediment yield. Chapter 4 describes specific steps in estimating yield and developing inflowing load and grain size distributions for sedimentation models. Procedures for evaluating the reliability of yield estimates can be found in Chapter 5 and Chapter 6 presents a detailed example application. References are listed in Chapter 7.

Considerable information is available on estimating the sediment yield from a watershed using both empirical methods and land surface erosion theory (Haan et al., 1994, Barfield et al., 1981, Kirby and Morgan, 1980, and Tatum, 1963). The same is true for quantifying sediment transport and sorting processes in rivers. This report presents a brief summary of land surface erosion computation methods and their use for developing the total inflowing sediment load for river sedimentation models such as HEC-6.

The limitations of currently available methods and their ranges of applicability are presented, and procedures for evaluating computed results for watershed erosion and sediment transport modeling are described. Included herein are the results of an assessment of numerical models for the prediction of land surface erosion. It was concluded from this assessment that these models have not yet evolved from the experimental/developmental phase to routine engineering use. Therefore, this document presents a strategy for the use of several traditional methods of computation of land surface erosion to prepare inflowing sediment loads for operation of HEC-6.

1.2 Definitions and Terminology

It is essential that terms used in sedimentation discussions be clearly defined to avoid confusion in narrative descriptions and computations. Therefore, the brief discussion that follows defines several key terms used later in this document. Additional terms and definitions are included in the Glossary found in Appendix B.

Soil erosion is the gross amount of soil moved by the action of wind and water. Soil erosion includes detachment, transport and subsequent deposition processes. Erosion is the process that displaces soil particles from their position on the ground surface, after which they may be transported by sheet flow in overland or interrill areas or in small concentrated flows in rills. Rills are very small channels which form in exposed soil due to concentrations of runoff. Rills combine to form small channels and streams which increase in size as tributary area increases. Deposition of the materials eroded from a watershed can be

temporary or long-term, depending on how and where within this watershed system the materials are trapped or deposited. Sediment production is the total amount of sediment resulting from surface erosion and various mass movements within a given watershed. Drainage density is the average stream length per unit of drainage area and is an important geomorphic and hydrologic characteristic of a watershed.

Sediment yield is the amount of sediment passing a specific location over a specified time, and the sediment delivery ratio (SDR) is the ratio of sediment delivered at a basin outlet to the total sediment production within a basin. Typically, SDR goes down as the size of the basin goes up. Sediment delivery is reduced in larger basins because there are usually more opportunities for sediment to be temporarily or permanently trapped. Water column sampling can provide suspended sediment concentration data, which when combined with river discharge can provide an estimate of suspended sediment load. A suspended sediment load rating curve relates suspended sediment load to river discharge at a particular location in the watershed. Sediment load is the mass or volume passing a location in the stream in a unit of time. Sediment loads in river channels vary with discharge, and total amounts of sediment passing a given point may be described as an average annual quantity or as a single event quantity. These quantities can vary greatly from year to year and from storm to storm because they are directly influenced by antecedent and succeedent watershed and soil conditions during periods of runoff. Therefore, it is very important to establish a long, continuous data record for a particular basin in order to develop a dependable sediment yield forecast from measured data. One or a few years of record may not provide sufficient information regarding the range of variability in sediment production and yield possible in a basin.

A sediment budget is the quantitative accounting and expression of the various sources and sinks (storage location and amount) of sediment within a specified drainage area. A sediment budget may be developed for a specific single event (days or weeks), a season (months) or on an annual or longer term basis. A sediment budget should account for the eroded material from land surfaces by rain splash, sheetwash, gully erosion, bank failure, bed transport, mass wasting, anthropogenic and technogenic processes. It must also account for storage (loss) within the drainage area and export out of the drainage area through channel transport processes, including bed material, suspended and wash load.

Basin water budgets are important when developing basin sediment budgets. A water budget is the quantitative accounting and expression of water entering the basin by precipitation or flow from adjacent basins; that amount being stored within the basin, that amount lost to the groundwater or to evapotranspiration, and that which flows out of the basin as excess runoff in the channels and streams. Examination of both the annual water budget and sediment budget for a basin provides information necessary to estimate basin sediment yield. Refer to Chapter 3 of EM1110-2-4000 (USACE, 1989).

Vanoni (1975) defines sedimentation as the combined processes of erosion, entrainment, transportation, deposition and compaction. Total sediment load is the sum of suspended load and bed load, that is, the sum of all sediment particles moving in the water column and those rolling, sliding, or bouncing along the bed (see Figure 1.1 for graphical representation). In addition to classification by transport method (suspended vs. bed load), sediment loads are also classified by origin. The wash load consists of particles that are generally not found in appreciable amounts on the river bed, but are transported through a river reach from upstream. The amount and size of wash load materials are a function of

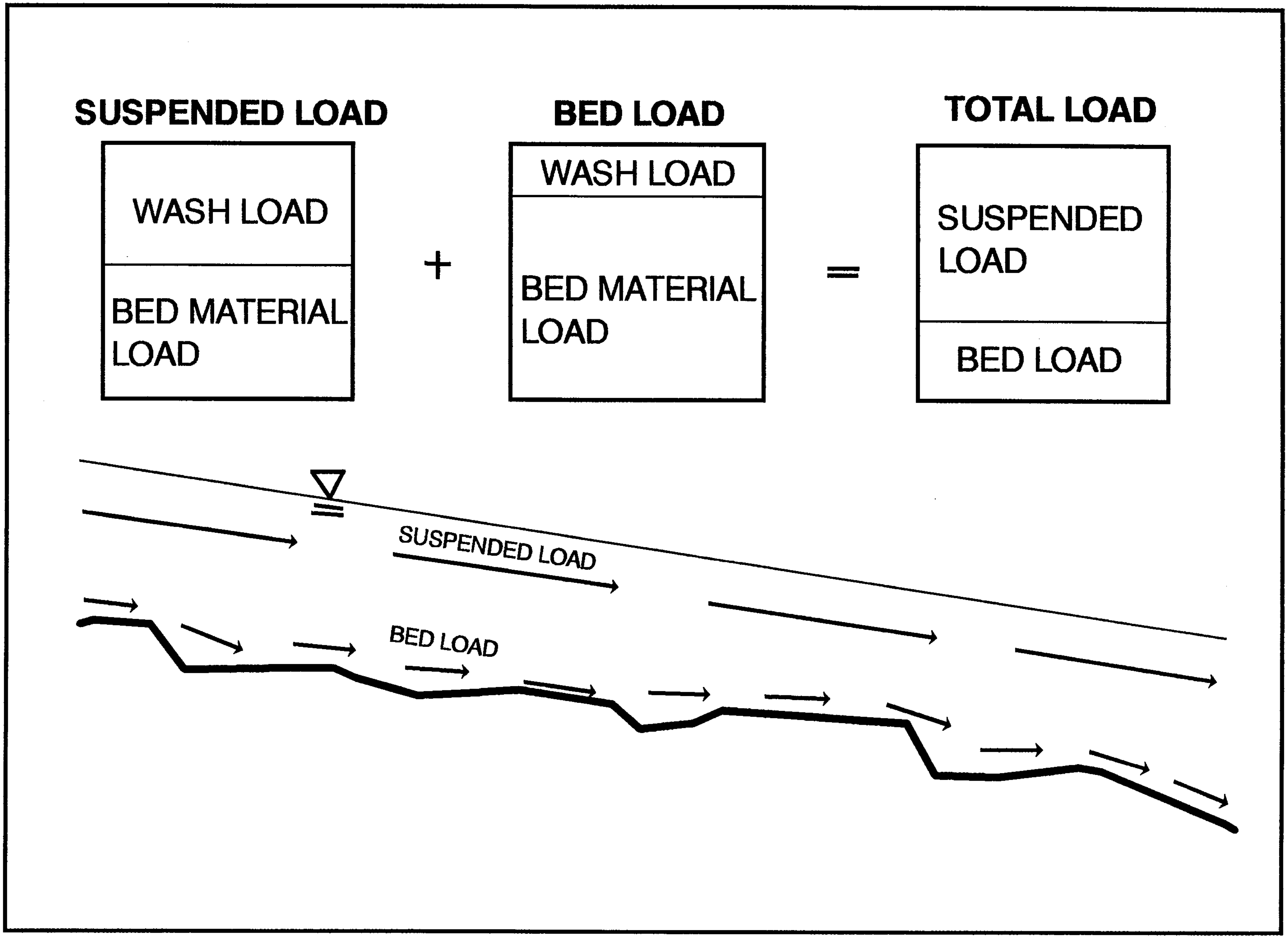


Figure 1.1. Types of Sediment Load

soils and watershed geomorphic characteristics and flow hydraulics. The bed material load is the portion of the load which is found in appreciable quantities in the river bed. It consists of the portion of the sediment load that rolls and slides along the bed plus that portion of the suspended load that interchanges with the bed in significant amounts. The wash load and bed material load may be transported partially in the suspended load and the bed load, although the wash load is primarily carried in suspension (Figure 1.1).

The distribution of particle sizes in the load is referred to as a gradation or grain size distribution. The sediment transport capacity of a stream refers to its ability to convey sediment of various sizes without deposition for a given flow condition. At high sediment concentrations, the increased volume of the water/sediment mixture is described by a sediment bulking factor based on the suspended sediment concentration by volume.

Appendix B provides a glossary containing more detailed definitions of terms typically associated with sedimentation studies.

1.3 Geomorphic Processes and Estimates of Sediment Yield

Sediment production and transport in a watershed are influenced by a complex set of geomorphic processes that vary in time and space. Important erosion processes include soil detachment through raindrop impact and overland flow, rill erosion and transport, gully erosion, channel degradation and bank erosion, various types of surficial gravity erosion, and wind erosion. Other processes that can contribute to the total watershed sediment production may include channel bank and hillslope failures, landsliding, forest fires, and debris flows. Land use practices such as logging and clearing, grazing, road construction, agriculture, and urbanization activities also affect sediment production and delivery from a watershed. Sediment production may vary significantly with long-term cycles in drainage system development and rejuvenation, and zones of sediment production and/or deposition may shift in location with time (e.g. headward movement of nick points and/or channel migration and avulsions).

Sediment transport is influenced primarily by the action of wind and water, and deposition occurs in a number of locations where energy for transport becomes insufficient to carry eroded sediments. Colluvial deposits, floodplain and valley deposits, channel aggradation, lateral channel accretion, and lake and reservoir deposits are examples of typical geomorphic deposition processes. The stability and longevity of sediment deposits vary. Lake and reservoir deposits tend to be long-term, whereas some channel and floodplain deposits may be remobilized by the next large scale flood event, only to be deposited downstream. The spatial and temporal variability of sediment production, transport and deposition greatly complicates the task of estimating sediment yield from a watershed.

Sediment yield, previously defined as the amount of sediment passing a specified channel location, is the product of a number of geomorphic processes combined, and may be substantially less than the amount actually eroded or produced in the basin. Sediment yield is typically expressed as the total sediment volume delivered to a specified location in the basin, divided by the effective drainage area above that location for a specified period of time. Yield typically has the units of $m^3/km^2/yr$ ($acre\text{-}ft/mi^2/yr$). For a specific basin, this can be converted to metric tons (Mg) or English tons(T) per year. However, it is also necessary to estimate yield from a watershed from individual storm events of specified frequency (e.g.,

5-, 25-, 50-, or 100-year events). Individual event yields are reported as metric tons (Mg) or cubic meters (m^3) per event. In flashy ephemeral watersheds, single event sediment yields often exceed average annual values by several orders of magnitude.

Spatial and temporal variations in physical and biological features of the watershed make estimation of sediment yield an extremely difficult and imprecise task. Important variables include soils and geology, relief, climate, vegetation, soil moisture, precipitation, drainage density, channel morphology, and human influences . Dominant processes within a watershed may be entirely different between physiographic or ecological provinces, and may change with time. The problem becomes even more complex when grain size distributions and sediment yield for particular events must be estimated for input to sedimentation models such as HEC-6 (HEC, 1993) and WES-SAM (WES, 1992). At the present time, there is no widely accepted procedure for computing basin sediment yield and grain size distribution directly from watershed characteristics without measured information. However, a variety of estimating procedures exist and several are discussed in this report.

Detailed discussion of each geomorphic process important to the determination of erosion, transport and deposition of sediment is beyond the scope of this study. However, Chapter 2 of this document presents a brief discussion of key geomorphic processes, their influence on sediment yield, and the corresponding limitations on current computational methods for estimating sediment yield.

1.4 Related Guidance Documents

Guidance documents relevant to sedimentation in flood control channels include the following:

Engineer Manual EM 1110-2-1601, Hydraulic Design of Flood Control Channels, 1991. This document deals with the hydraulics of fixed-boundary channels. Problems of erosion and sedimentation are presented in the context of riprap protection.

Engineer Manual EM 1110-2-4000, Sedimentation Investigations or Rivers and Reservoirs, 1989. This document deals with field and office investigations of sediment problems for a variety of projects including reservoirs, navigation channels and flood protection channels. The scope of the studies indicated may often be impracticable for smaller flood control channel projects.

Engineer Manual EM 1110-2-1205, Environmental Engineering for Flood Control Channels, 1990. This document deals with environmental factors to be considered in channel projects and with environmental features that can be incorporated in channel design.

Engineer Regulation ER 1110-2-1405, Hydraulic Design for Local Flood Control Projects, 1982. This document covers design rationale and process.

Engineer Manual 1416, River Hydraulics, 1993. This document covers the computation of uniform, non-uniform, steady and unsteady flow in rivers with fixed and movable boundaries.

Engineer Circular EC 1110-8-1(FR), Stability of Flood Control Channels, 1990. This document discusses the geomorphic and hydraulic characteristics of channel stability.

HEC-6 User's Manual, Scour and Deposition in Rivers and Reservoirs, CPD-6, 1993. HEC-6 is a one-dimensional mobile boundary open channel flow and sediment model designed to simulate changes in river profiles due to scour and deposition over fairly long time periods.

HEC Training Document No. 13 (TD-13), Guidelines for the Calibration and Application of Computer Program HEC-6, 1992. This document complements the HEC-6 User's Manual (HEC, 1993) and provides guidelines for calibration and application of HEC-6.

Chapter 2

Watershed Geomorphology

2.1 Geomorphic Processes

An understanding of key surface erosion and watershed geomorphic processes is essential to application of sediment production estimation techniques. In particular, the variability of these processes in space and time is important in establishing limitations on the accuracy of estimates derived from sediment discharge data and/or predictive models.

Physical processes produce sediment discharges which range from those which occur on a small scale, such as soil particle detachment by raindrops, to those which can occur on a massive scale such as landslides or debris flows. Erosion and sediment transport occur continuously in most watersheds, yet large fractions of the total sediment production in a watershed may be due to episodic events, especially in regions with moderate to arid climatologic conditions. Even under 'normal' conditions, large variations occur in the rate of sediment production and sediment delivery throughout a watershed.

Important physical processes that produce sediment include raindrop soil detachment and splash erosion, interrill erosion due to sheet flow, rill formation, gully formation and development, channel bed and bank erosion, and various types of mass movements along slopes. On very small scales of time and space, erosion rate is roughly equivalent to sediment yield. That is, the sediment delivery ratio (SDR) is unity. However, for larger basins, as the area and time scales to be considered increase, transport and deposition processes influence both the sediment yield and the timing of sediment discharge from a basin. Deposition occurs at the base of steep slopes; in lakes, reservoirs, and wetlands; in river flood plains; and on point bars in stream channels (lateral accretion and bed aggradation). Deposition can be temporary or long term. Although typical erosion and deposition processes are generally familiar and fairly easily understood, the interplay of factors that influence sediment yield from a watershed is less obvious and much more difficult to estimate quantitatively.

Episodic and spatially varying processes dominate sediment and water flow, but theories and quantification of these processes are not well developed. Biota play essential roles in the production, transport and storage of sediment and water, but knowledge of biological functions is poorly integrated into quantitative procedures for estimating sediment and water budgets. The relationship of hydrologic and sedimentation processes to seismicity, tectonism, and mass wasting is also poorly understood.

2.2 Physiographic Provinces

On a geologic time scale, the surface of the earth is transformed by sediment production (erosion) in the upper part of a watershed, transportation of sediments in a fluvial system, and deposition in low-lying lakes, alluvial fans, deltas, and in the oceans. For the purposes of describing sediment yield, it is instructive to divide a watershed into major zones

or provinces where different sets of physical processes interact to characterize sedimentation processes. Schumm (1977) presented a generalized fluvial drainage basin divided into three physiographic zones. A typical basin is divided into a production zone (Zone 1, sediment source area), transfer zone (Zone 2), and deposition zone (Zone 3, sediment sink area).

USACE (1990) proposed a refinement of Schumm's definition which further classifies zones according to dominant local sediment transport processes, and characterizes relative amounts of different sediment sizes within the regions. Figure 2.1 shows an idealized classification system. Figure 2.2 shows how the three major physiographic zones connect to each other (Figure 2.2a) and how the longitudinal profile of the stream system tends to flatten through time by degradation in the upper watershed and aggradation in the lower watershed (Figure 2.2b). Development of basin sediment budgets and yield estimates requires an understanding of how these zones or provinces connect and the approximate quantities of materials entering and leaving each zone for the expected range of flow conditions. Figure 2.3 presents photos of the typical characteristics found in a source zone where active sheet, rill, gully and channel erosion combine with mass wasting to deliver sediment to a river.

It should be noted that any representation of physiographic provinces in a watershed is necessarily an oversimplification. However, these zones are useful for visualization of dominant processes which affect sediment yield at different points in a watershed. A single physiographic model is, of course, not applicable to all watersheds, and the arrangement of erosional, depositional, and transport regions will be unique to each basin. Even with this simplified physiographic model, the sediment production and transport system is still extremely complex, involving the interaction of many hydrologic and geomorphic processes.

2.3 Production Zone

For the purpose of estimating sediment production, important processes can be roughly divided into three categories of sheet and rill erosion, gully and channel erosion, and mass wasting processes. The relative magnitudes of each category depend on the soils, geomorphic, hydrologic and land use characteristics of the basin. Changing basin conditions also affect annual sediment production and yield.

2.4 Sheet and Rill Erosion

Sheet (interrill) and rill erosion occur as the result of raindrop impact and runoff on the earth's surface. Investigators have developed numerous physically-based relationships for describing interrill sediment detachment and transport (Yalin, 1963, Palmer, 1965, Young and Wiersma, 1973, Mutchler and Young, 1975, and Walker et al., 1977). This research indicates that (1) interrill transport differs from channel transport in that soil surfaces in interrill areas are generally more cohesive than alluvial bed material (including the effect of binding by vegetation); and (2) transporting force is supplied by both overland flow and raindrop impact energy. Guy et al. (1987) found that up to 85% of the erosion in interrill areas is attributable to raindrop impact, depending on rainfall intensity and land slope.

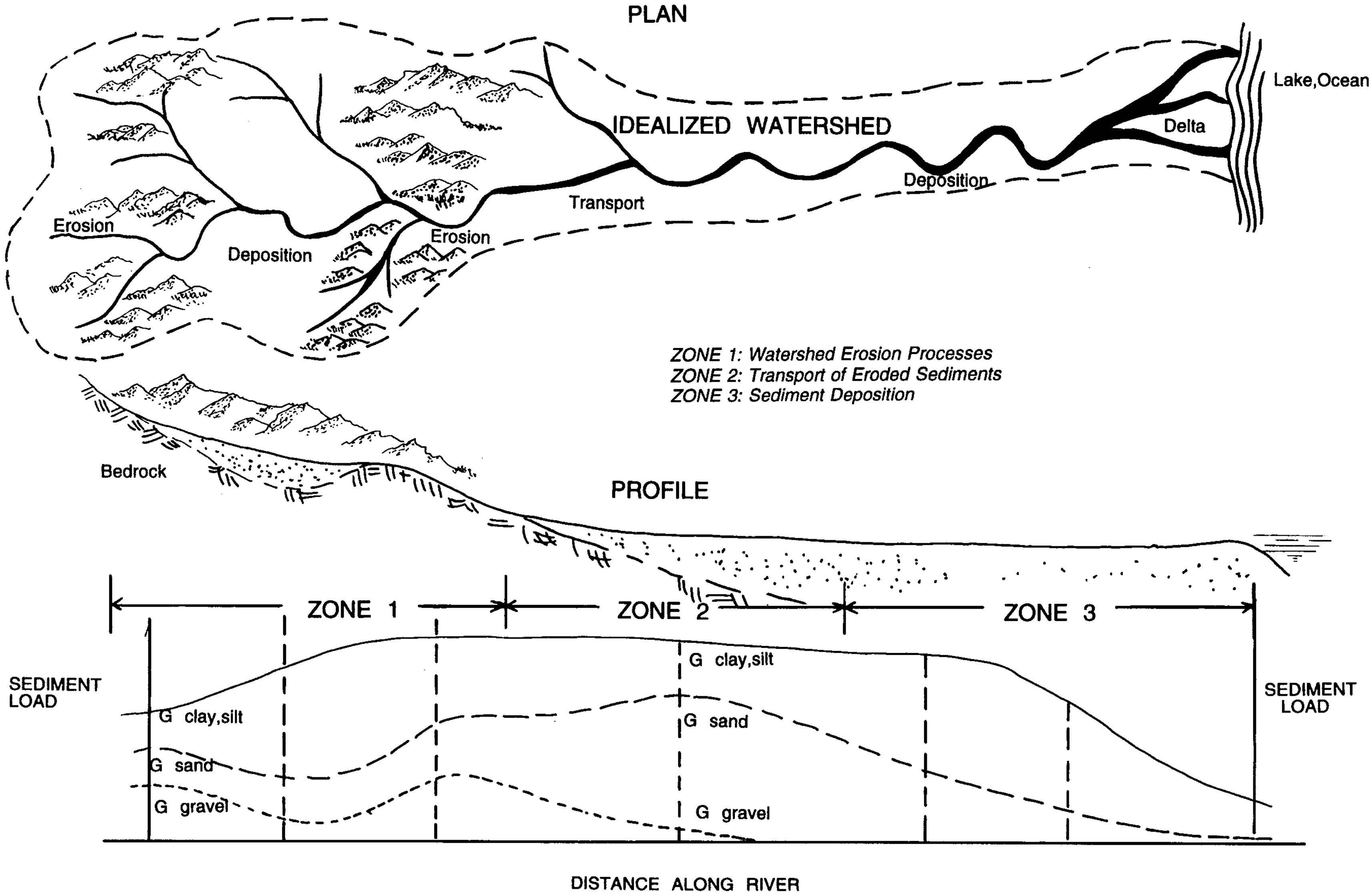


Figure 2.1 Classification of Alluvial Channel and Major Physiographic Provinces

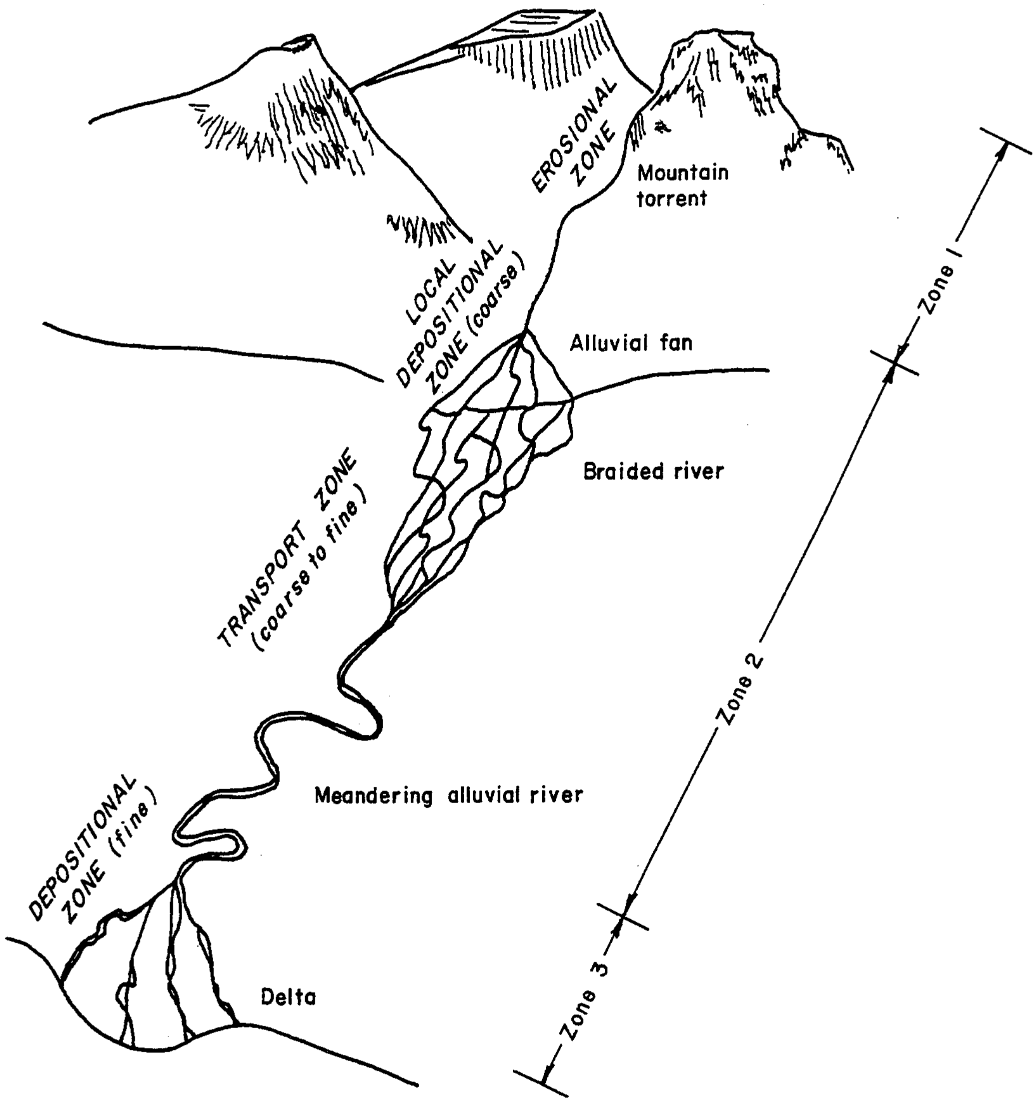


Figure 2.2a – Drainage Basin Zones and Some Channel Types

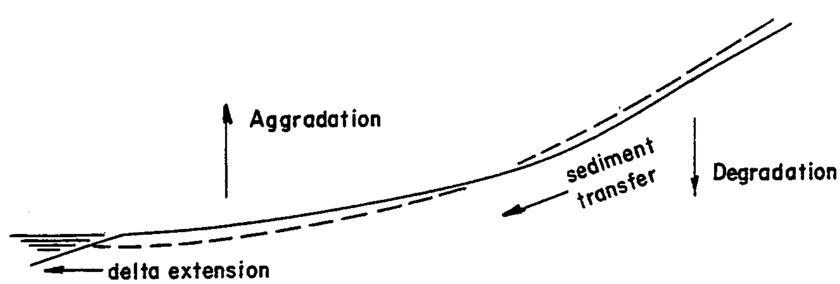


Figure 2.2b – Typical Longitudinal Stream Profile and Direction of Change Through Time

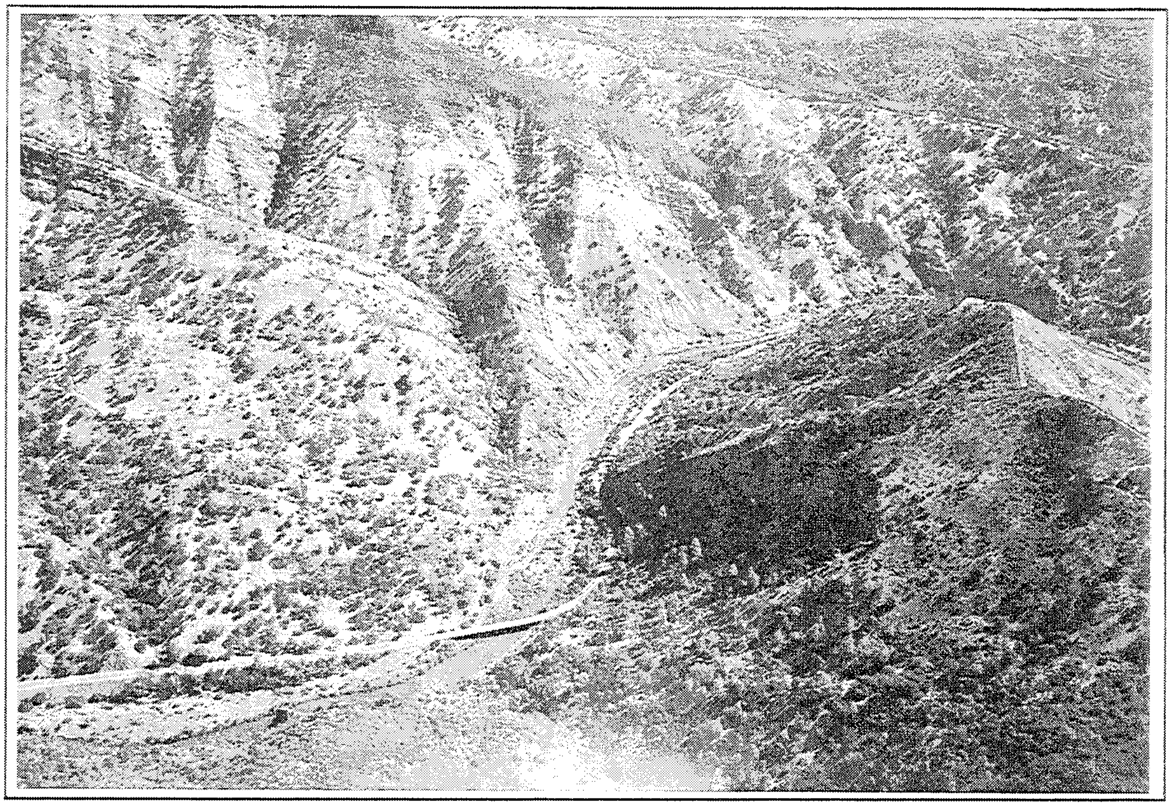


Figure 2.3 Sheet, Rill, Gully, and Channel Erosion Combined with Mass Wasting in the Source Zone of Cache Creek, CA

Researchers have also investigated the development of hillslope rills and their role in sediment production and transport. Rills are generally defined as very small channels which could be removed by normal tillage. For non-agricultural watersheds, they can be considered transient channels which would not persist through seasonal or long-term land forming processes. Govindarajv et al. (1991) measured rill development on a freshly cut slope of decomposed granite. The experiment concluded that flow and sediment transport in rills was prominent in relation to overland flow areas, and that the use of sheet flow models at the hillslope scale may drastically underestimate sediment production.

Sheet and rill erosion are significantly influenced by topography (slope and aspect), soil type, vegetative cover, and land use. Slope length and gradient are primary factors which determine the energy available for soil particle detachment and transport. Soil type influences resistance to detachment and rill development. Vegetation has a significant impact on resistance to erosion, and also effects raindrop energy. Vegetation in the form of canopy or ground cover intercepts rainfall kinetic energy and distributes flow to the ground surface. Land use, especially disturbances such as logging, grazing, road building, and mining, agriculture, and urban development, can significantly affect rates of sheet and rill erosion through changes in topography, soil characteristics and vegetation. Readers should refer to Haan et al. (1994), Barfield et al. (1981), and Kirkby and Morgan (1980) for more information on the specific effects of soil, land use and topography on sheet and rill erosion rates.

2.5 Gully and Channel Erosion

Gullies are often defined as small channels that cannot be removed by normal tillage practices. From a more geomorphic perspective, gullies are defined by Schumm et al. (1984) as relatively deep, recently formed eroding channels where no well-defined channel previously existed. This definition points out that gullies are characteristic of a changing drainage network, and emphasizes their unstable nature. Gullies are often associated with drainage system rejuvenation due to base level lowering, or changes in hydrologic or watershed conditions. Gully erosion can produce tremendous sediment loads from relatively small drainage areas; however, the contribution to the total sediment yield for basins larger than 10 square miles may be small. The Soil Conservation Service (SCS) is often an excellent source for information regarding local gully erosion rates.

Advancement of gullies in the drainage network seems to follow a consistent evolution toward more stable conditions, in spite of diverse gully morphologies and climatic conditions. However, this evolution is normally complex and episodic in nature, and the drainage system may progress through cycles of adjustment before reaching more stable conditions.

Drainage system rejuvenation can dramatically influence sediment yield, especially in arid and semi-arid climates. Sediment production can be highly variable under these conditions, and some areas of the watershed may be out of phase in terms of sediment production, with others (Schumm et al., 1984). Therefore, where gullying and drainage system rejuvenation are taking place, it is important when making estimates of sediment yield, that the drainage system be considered from an evolutionary perspective.

Instantaneous measurements of sediment yield may not actually represent sediment yields over long-term, geomorphic evolution of the drainage system.

River channel erosion is another potential source of sediment, although for relatively stable channels this source is likely to be significantly less than land surface and gully erosion. However, for drainage basins where significant river bank or bed erosion is occurring, this source should be included in sediment yield estimates. For long-term estimates, it may be necessary to consider the possibility of avulsive channel adjustment and the quantity of material that might be produced by large, episodic changes in channel form and possible channel relocation. The causes of stream bank erosion, bank caving and avulsion are many and varied, and the prediction of future losses at specific locations is difficult. No generalized analytical procedures have yet been developed to formally calculate sediment yield or specific bank line losses from stream bank erosion. The most successful methods are based on the analysis of time series of aerial photographs to quantify the extent and rate of bank loss with time.

2.6 Mass Wasting

Leopold et al. (1964) provide a classification of mass movements into falls, slides and flows. Hillslope processes contribute to sediment production on both a continuous and episodic basis. Because many continuous hillslope processes (except sheet and rill erosion) are not directly connected to the fluvial system, their contribution to sediment load in streams may be relatively difficult to distinguish. However, extreme or episodic hillslope processes such as landslides and debris flows have a direct relationship to hydrologic conditions and events. Especially where sediment loads must be estimated for extreme hydrologic events, the probability of large mass movements and their potential for sediment production must be considered.

Various mass wasting and hillslope processes affect watershed sediment production. Figure 2.3 shows an active hillslope (mass wasting) failure zone adjacent to a creek.

Occasional hillslope failures can be sources of significant volumes of sediment and usually enter the river system as large pulses during a significant rainfall/runoff event. The frequency with which mass wasting events occur within a basin greatly affects both single event and annual sediment yield values. Geomorphic field studies may be required to estimate the frequency and relative sediment loads periodically produced by these types of events.

In watersheds disturbed by influences such as logging, overgrazing, or fire the likelihood of mass movements is greatly increased. The degree to which sediment from mass movements is transported to the fluvial system depends on general climatic and geologic conditions, and on the physiographic location of the sediment producing process in relation to the drainage system.

2.7 Transport Zone

The transport zone (Zone 2 in Figure 2.2) is dominated by fluvial transport processes which vary with time. Where the sediment production in the upper part of a watershed is relatively low compared to the transport zone capacity of a stream or river, a large percentage of the sediment produced will be realized as sediment yield at the downstream end of the transport zone. However, in basins of appreciable size, either temporary or long-term storage of sediments will likely occur in the transport zone. Examples of this type of storage within the fluvial system include river point bars, mid-channel bars, and river braiding. Figure 2.4 shows an aerial photograph of a transport zone on the Sacramento River with transient depositional features.

Long-term discharge and sediment load characteristics are key determinants in channel morphology. Alluvial channels tend naturally toward a state of dynamic equilibrium based on these characteristics. Figure 2.5 illustrates river channel types for gravel bed rivers related to sediment load. Assuming a channel is in a state of relative equilibrium, no net loss or gain of sediments will occur in the transport zone over the long term. However, in the short term, changes in sediment storage in the transport zone can be significant, and will affect sediment yield on an event basis.

Most of the sediment transported by a stream is in suspension (see Figure 1.1), with only about 5 to 15 percent of the total transported as bed load (Vanoni, 1975). Sediment transport capacity is a power function of discharge. Therefore, sediment tends to be moved episodically, particularly the large particle sizes in the bed load. Since channel shape changes primarily in response to bed load transport, it is determined by relatively infrequent events with high sediment transport rates. Changes in channel shape or location represent large changes in sediment storage volume in the transport zone, and thus are sources of sediment for particular events.

Where the fluvial system has been disturbed from dynamic equilibrium, changes can be expected in the channel's shape, depth and location as it attempts to establish a new equilibrium. These changes may result in a net loss or gain of sediment in the disturbed reach over a substantial period of time. For example, channels affected by instream gravel mining often respond by incising (bed degradation), resulting in bank erosion and lateral instability (Collins and Dunne, 1990). These types of effects can represent a significant long-term source of sediment.

Potential significant sources of sediment in the transport zone include:

1) bed and bank erosion
2) channel avulsion
3) large episodic or seasonal changes in channel morphology

These factors are particularly significant for estimates of sediment yield by event, since large events are most likely to result in changes in channel form. Geographic areas with large seasonal or short-term variation in discharge (e.g., the southwest United States) experience the greatest episodic adjustments in channel form.

Figure 2.4

Transport Zone of Sacramento River, CA
Showing Transient Depositional Features

gravel supply
lateral instability
valley slope
ratio bedload to total load

low — high

TYPE	IRREGULARLY	MEANDERING	WANDERING	ANASTOMOSED	BRAIDED
PATTERN	straight,sinuous irregular	irregular or regular meanders	irregular	irregular	straight
ISLAND	none occasional	occasional	frequent, regular or irregular to spilt	split to anastomosed	none
BARS	none, side bars diagonal	diagonal, point bars	diagonal, point mid-channel	diagonal, point mid-channel	diamond mid- channel braided
LATERAL ACTIVITY	none, limited	downstream progression	irregular avulsion	avulsion irregular	avulsion
SOURCES	Kellerhals, 1967	Carson, 1987	Neill, 1975 Church, 1981	Smith, 1983 Galay, et al. 1983	Carson, 1987 Fahnestack,1963

Figure 2.5 River Channel Types and Their Relationship to Gravel Supply, Lateral Stability, Valley Slope and Ratio of Bed Load to Total Load

For the purposes of estimating sediment yield, transport zone processes influence the quantity and timing of sediment discharge. It may be necessary to estimate the quantities of material that are temporarily deposited and stored in river reaches during periods of relatively low discharge, and the amount that can be subsequently remobilized and removed from the transport zone during large runoff events. Examination of the physical characteristics of a transport zone channel can be used to determine whether changes in sediment storage will make a significant contribution to sediment yield. Where sediment supply temporarily exceeds transport capacity, it will be reflected in channel morphology. The most notable example of this condition is a braided river reach (Figure 2.5).

Braided river reaches are depositional regions within the transport zone, and differ from the true depositional zone (Zone 3 in Figure 2.2) in that sediment may be stored temporarily (in channels and other geomorphic features such as alluvial fans), and then be remobilized and moved through the transport zone by very high discharges. As shown in Figure 2.5, the characteristic features of the river through a braided reach are multiple channel patterns (frequent islands and/or bars); eroding, unstable banks; and bed material being coarse (cobbles, gravel) at the upper end of the reach and transitioning to sand or fine gravel at the lower end of the reach.

The braided deposition reach is often developed as an alluvial fan whenever its lateral shifting process is not confined. Slopes on an alluvial fan can be as little as one-tenth the slope of the river emerging from a mountain gorge - this means that bed load transport capacity can be reduced by as much as 50 times. The abrupt reduction in bed load transport capacity results in coarser materials being deposited rapidly through the reach of reduced slope. Due to high amounts of episodic deposition and subsequent remobilization, a braided channel pattern results. Gravel is often no longer present in the river bed at the end of the braided deposition reach. The pattern downstream of the deposition reach often changes to a meandering channel, and may become a transport reach having sand as the predominant bed material.

The reduction in bed load through the braided (depositional) reach results in multiple channels which change size and shape. The change in river morphology can be inferred from the "river channel types" chart presented in Figure 2.5. Sediment supply, lateral instability, valley slope and the rates of bedload to total load, increase from left to right. The most laterally unstable, highly avulsive channels have high bed load to total load ratio, steeper slopes and higher total sediment loads.

2.8 Episodic Sediment Production

Although sediment production occurs continuously, extreme hydrologic events may represent a disproportionate share of total long-term sediment production in many watersheds. Wolman and Miller (1960) showed that for a large number of both small and large watersheds, a large fraction of the total sediment discharged occurs over a small percentage of the total time. This is especially true in semi-arid and arid regions, where more than 99% of the sediment movement can occur during very infrequent runoff events. For a study of the Kiowa Creek, Colorado drainage area, approximately 50% of the sediment was discharged over 0.3% of the time. The episodic nature of sediment production in a watershed varies with its physical and hydrologic characteristics. Neff (1967) found that arid

regions differed significantly from humid regions in this respect, presumably due to differences in soils, vegetative cover, and rainfall patterns. In arid regions, only 40% of the long-term sediment yield was produced by runoff having a frequency less than 10 years; in humid regions, over 90% of the yield was produced.

Episodic events such as landslides, debris flows, and channel avulsion can significantly influence long-term sediment yield. Spatial and temporal variability of sediment production can be especially significant in arid and semi-arid climatic regions. Sediment yield may be low or moderate during more frequent hydrologic events due to limited production or transport (low sediment delivery ratio). However, once the magnitude of a storm event exceeds a critical threshold, the sediment that has been temporarily stored in the watershed and channel system can be added to that produced by the storm and transported downstream. These effects can easily be missed in short-term sediment sampling programs or in estimates of sediment production based on simplified sheet, rill, and channel erosion methods. However, these episodic loads represent important design conditions for channels and reservoirs, and are often a significant fraction of the annual sediment yield. In watersheds with highly variable episodic sediment discharges, it may be better to represent the sediment yield of a watershed as a range of possible annual yields for low, medium and high production periods, rather than a single average value. (MacArthur et al., 1990). Geomorphic field investigations may be required to determine the relative contribution from these types of events. Comparison of reservoir hydrographic surveys in the basin before and after large runoff events is also very useful.

Wash loads are generally governed by sediment production in the watershed. In contrast, bed material load is more related to the transport capacity of the channel. However, wash load concentration can affect bed material transport capacity (Vanoni, 1953). During extreme hydrologic events, wash load concentrations increase dramatically, especially in disturbed watersheds or where mass wasting processes are significant. In extreme cases, sediment load may increase beyond the streams' ability to convey it, at concentrations on the order of 100,000 ppm. A limiting concentration such as this, based on channel gradient and shape, may define the upper limit of single event sediment load and yield.

2.9 Effects of Watershed Disturbance

Human and natural disturbances can increase erosion rates by orders of magnitude. Examples of human disturbance include logging, road building, mining, agriculture, and urban development. Natural disturbances can include seismic activity, volcanic activity, and fire. Sediment produced from disturbed areas within a watershed can far outweigh that from undisturbed areas in determining sediment yield.

In recent years, human disturbance has become the focal point of water quality protection efforts in the National Pollution Discharge Elimination System (NPDES). Best Management Practices (BMP's) are being implemented in watersheds across the country to reduce sediment production and transport. Therefore, estimation of sediment yields from disturbed watersheds often involves estimating both the effects of disturbance and installed sediment control techniques.

Fire dramatically changes the vegetation and soils of a watershed. Fires increase the magnitude of floods, increase the erodibility of soils, and contribute to the probability of catastrophic events such as debris flows and landslides. A fire initiates a process of soil erosion which continues through subsequent storms as dry sand and gravel fills swales and channels, is transported off the site, and new rill patterns and channel networks develop. Data from chaparral watersheds in Southern California indicate that sediment yield can increase more than 100 times after a fire (MacArthur, 1983). Recovery of pre-burn conditions can take several years, and the response of the watershed land surface may be out of phase with that of the channels (Heede et al., 1988).

Nasseri (1988) showed that flood frequency estimates may need to be modified to account for the effect of fire in chaparral watersheds. Similar adjustments may be appropriate for estimating long-term sediment discharge.

2.10 Data Sources

Data for use in the development and/or evaluation of yield estimates may come from office files, other federal agencies, state or local agencies, universities and consultants, making the field reconnaissance of the project site and study reach, surveys initiated specifically for the study, etc. Investigators are encouraged to seek data and advice from the following sources.

2.10.1 U.S. Geological Survey (USGS)

USGS topographical maps and mean daily discharges are used routinely in hydraulic and hydrology studies and are also common data sources for sediment studies. Mean daily flows, however, are often not adequate for sediment studies. Data for intervals less than one day or stage-hydrographs for specific events, if needed, can be obtained from strip-chart stage recordings that are available by special request. It may be preferable to use USGS discharge-duration tables rather than developing in-house; these are available from the state office of the USGS. Water quality data are sometimes available and inlcude suspended sediment concentrations for each year and for the period of record. Also available, are periodic measurements of particle size graduations for bed sediments.

2.10.2 National Weather Service (NWS)

There are cases when the mean daily runoff can be calculated directly from rainfall records and expressed as a flow-duration curve without detailed hydrologic routing. In those cases, use the rainfall data published monthly by the National Weather Service for each state. Hourly and daily rainfall data, depending on the station, are readily accessible. Shorter interval or period-of-record rainfall data can be obtained from the NWS National Climatic Center in Asheville, North Carolina.

2.10.3 Soil Conservation Service (SCS)

The local SCS office is a good point of contact for historic land use information, estimates of future land use, land surface erosion, and sediment yield. They have soil maps, ground cover maps, and aerial photographs which can be used as aids to estimate sediment

yield. Input data for the Universal Soil Loss Equation is available for much of the United States. The SCS also updates reservoir sedimentation reports for hundreds of reservoirs throughout the country every 5 years, providing a valuable source of measured sediment data.

2.10.4 Agricultural Stabilization & Conservation Service (ASCS)

This agency of the Department of Agriculture accumulates aerial photography of crop lands for allotment purposes. Those photographs include the streams crossing those lands and are, therefore, extremely valuable for establishing historical channel behavior because overflights are made periodically.

2.10.5 Corps of Engineers (COE)

Because the Corps gathers discharge data for operation of existing projects and for those being studied for possible construction, considerable data for a particular study area may already exist. The Corps has acquired considerable survey data, aerial and ground photography, and channel cross sections in connection with floodplain information studies. Corps laboratories have expertise and methods to assist in development of digital models.

2.10.6 State Agencies

A number of states have climatologic, hydrologic, and sediment data collection programs. Topographic data, drainage areas, stream lengths, slopes, ground cover, travel times, etc. are often available.

2.10.7 Local Agencies, Universities, Consultants, Businesses, and Residents

Land use planning data can normally be obtained from local planning agencies. Cross section and topographic mapping data are also often available. Local agencies and local residents have, in their verbal and photographic descriptions of changes in the area over time, information that is most valuable to the engineer. This source may include descriptions of changes associated with large flood events, incidents of caving banks, significant land use changes and when these changes occurred, records of channel clearing/dredging operations, and other information. Newspapers and individuals who use rivers and streams for their livelihood are likewise valuable sources for data.

A number of published sources of measured suspended load and bed load data for large drainage basins located in California, Oregon and Washington are listed in Appendix C.

Chapter 3

Methods for Estimating Sediment Yield

3.1 Background

In the United States, soil erosion and soil losses from watersheds were first investigated intensively in association with agriculture. Tillage was found to dramatically increase erosion rates and thus loss of valuable agricultural soils. Early estimates were based on observations that various cultural and land use practices differed in their ability to control soil erosion. These initial estimating procedures involved single factor equations to represent local conditions where other contributing factors were nearly constant. Multiple factor relationships were developed as more data became available and researchers were able to describe multiple contributing factors. A variety of field-plot erosion studies were carried out beginning in 1917 (Smith, 1966), to attempt to quantify erosion rates based on precipitation, crop patterns, soils, and slope characteristics. Zingg (1940) related soil loss to slope steepness and length. Soil erodibility and land management practices were later incorporated into quantitative techniques (Smith, 1941, Smith and Whitt, 1947, and Van Doren and Bartelli, 1956). Musgrave (1947) added a rainfall parameter to develop an empirical relation using factors for erodibility and vegetative cover, the land slope and slope length, and the 30-minute, 2-year frequency rainfall amount.

The Universal Soil Loss Equation (Wischmeier and Smith, 1960) was developed to overcome deficiencies in Musgrave's equation in predicting erosion rates by storm, season, or crop year based on average annual rainfall patterns. The USLE became the basic equation for estimating soil loss from sheet erosion, and data for estimating the various factors were tabulated for a wide variety of field conditions and geographic locations. Revisions of the USLE (MUSLE, RUSLE) have been developed to extend its applicability (Williams, 1975 and Weltz et al., 1987). The general accuracy of the USLE equation for estimating soil loss from field plots has been confirmed by a large number of data in various environmental conditions (Vanoni, 1975), however, its applicability to complex watersheds has been questioned (Haan et al., 1994).

Although sheet and rill erosion are primary sources of sediment in most watersheds, other sources as described in Chapter 2 may be significant. In addition, transport of eroded sediments downstream to a specified point is influenced by a complex set of interacting geomorphic processes including erosion, entrainment, transportation, deposition and compaction.

Researchers have focused on development of physically-based relations to replace the empirical form of the USLE for computation of sheet and rill erosion. However, the application of physically-based models to complex watersheds is not a common practice. Physically-based models typically contain equations with constants and exponents which must be determined for each watershed or basin and location-specific hydrologic conditions, and the data requirements are often overwhelming. A variety of empirical and semi-empirical models have also been developed and utilized. Refer to Appendix A "Progress Report on Land Surface Erosion," for a summary of several of the more common models.

Attempts are currently underway by researchers to combine soil loss and hydrologic models so that sediment movement within and from watersheds can be estimated. However, no single numerical modeling technique has emerged as a suitable technology for use in estimating sediment yield for the purposes of river or reservoir sedimentation studies.

Many of the existing models were developed for application to agricultural lands and have limited applicability in other types of watersheds. Furthermore, calibration data is often unavailable, or available only for moderate hydrologic conditions. The applicability of these models to extreme hydrologic events, typically required in many Corps of Engineers analyses, would be extremely limited due to the lack of calibration data. Because erosion and sediment transport processes are not fully described as yet, a process-based sediment yield estimation procedure is not likely to be developed for some time.

3.2 Recommended Approach to Sediment Yield Estimation

In practice, sediment yield must often be estimated on an average annual or single event basis for complex watersheds with limited available data. A general approach in use by many investigators is to utilize a number of techniques to estimate yield, and then cross-check results against one another and against engineering judgement. In the absence of a verified, widely applicable specific technique, this approach is recommended.

Investigators should select techniques for estimation of sediment yield based on an understanding of the dominant geomorphic and hydrologic processes occurring in a watershed. Particular attention should be given to determining which sources of sediment are likely to be predominant, and the ability of the drainage system to transport produced sediment to the point at which yield must be estimated.

Selected techniques will vary depending on the purpose of the investigation and the availability of measured data. For example, estimation of single event sediment loads in a river channel for an extreme hydrologic event may differ significantly from average annual estimates.

In general terms, total sediment yield can be estimated by summing potential sources and then reducing the estimate to reflect the transport capability in the fluvial system. This general approach is illustrated in Figure 3.1.

3.3 Estimating Sediment Sources

For each of the categories shown in Figure 3.1, several potential methods are available for use in qualitative estimates. Multiple methods should be selected for comparative purposes. Selection of methods should be based on their applicability to particular type of problems, or geographic areas, and the investigators' familiarity with the methods. Because all of the methods involve judgement in selection of parameters, familiarity with application of a particular method is an important consideration.

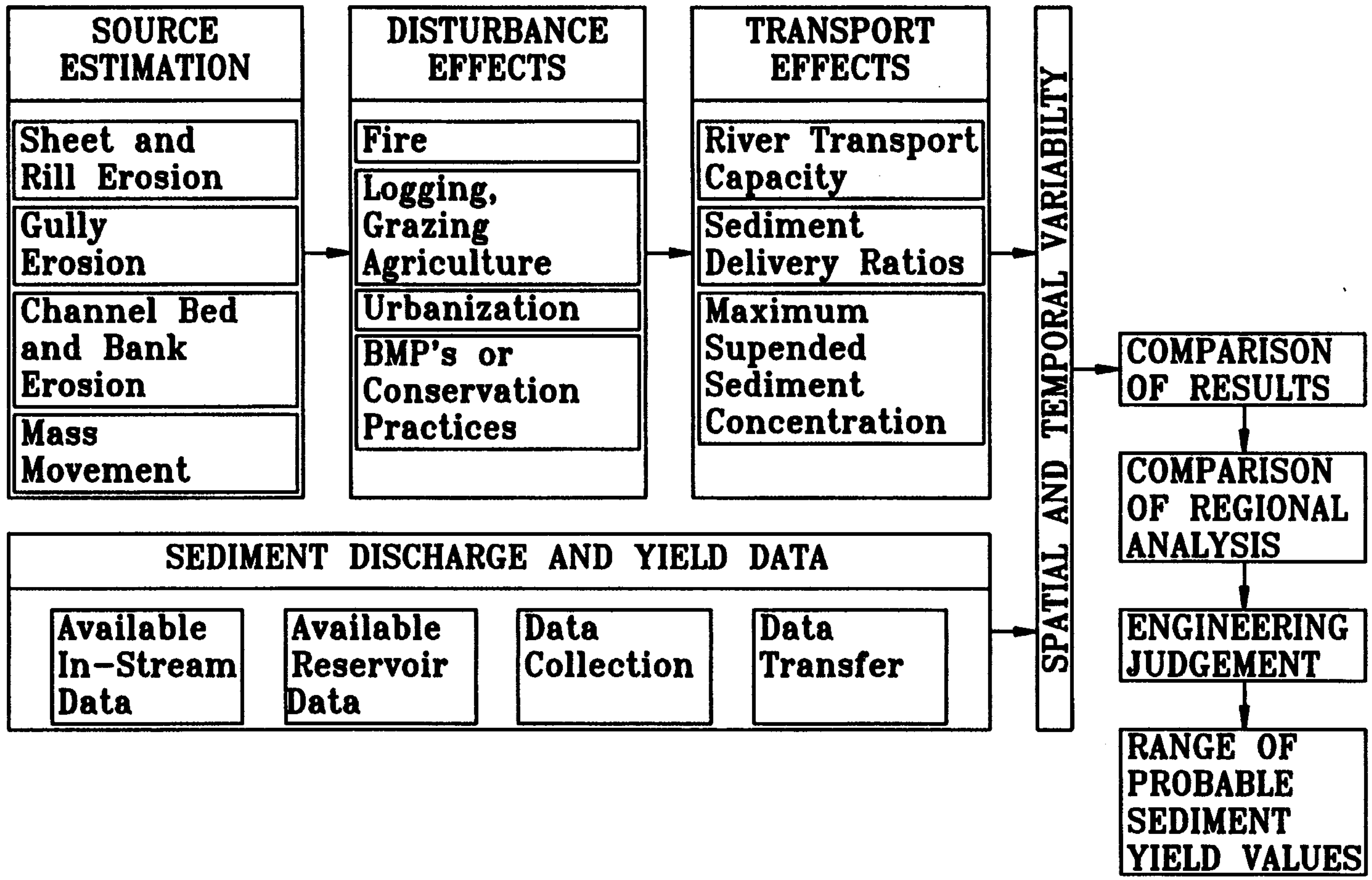


Figure 3.1 – Schematic Representation of Estimating Sediment Yield

5002.3-1.1.2

Table 3.1 lists estimation techniques that may be considered for particular applications. The table includes several empirical computation methods, two comparative methods (aerial photography and topographic surveys), and three regional relationship methods (Dendy and Bolton, 1976, Strand and Pemberton, 1982, and SCS Yield Rate Maps and local or regional soil loss/yield rate estimates from soil and water conservation agencies). Several of the methods are briefly described below.

Table 3.1
Sediment Source Estimation Techniques

Method	Sheet and Rill Erosion	Gully Erosion	Channel Bed and Bank Erosion	Mass Movement	Average Annual Yield	Single Event Yield
USLE					*	
MUSLE						*
BUSCLE					*	
PSIAC					*	
Aerial Photography					*	*
Topographic Surveys					*	*
Thompson or SCS TR32					*	
Dendy and Bolton					*	
Strand and Pemberton, USBR					*	
SCS Yield Rate Map					*	

3.4 USLE Method

The Universal Soil Loss Equation (USLE) is perhaps the most widely used method for estimating soil erosion. The equation was originally developed for application to agricultural fields, but its use has been greatly extended in practice. The USLE was derived for estimating average annual yield, and not single event volumes. In spite of its wide historical application, investigators should be careful to recall that the equation was intended for estimation of sheet and rill erosion, on relatively small agricultural plots. Its accuracy for application to complex watersheds, especially for forest and rangeland, depends on the experience of the user. However, the method has the advantage that large amounts of data are available for parameter estimation based on practice. (See Kirkby and Morgan, 1980, Haan et al., 1994 and Barfield et al., 1981.) The equation has the form

$$A = R * K * LS * C * P \tag{3.1}$$

where:

A = average annual sheet and rill erosion (mass/area)
R = Rainfall erosion index (length*mass/area*intensity)
K = soil erodibility factor (mass/area/unit of R)

LS = slope length and steepness factor (dimensionless)
C = vegetative cover factor (dimensionless)
P = erosion control practice factor (dimensionless)

The equation has traditionally been applied in English units, and the various factors contain some embedded units based on experimental methodology. Therefore, application of the equation in English units, and conversion of the results to metric units may be more practical than conversion of all the factors to metric units. To calculate erosion, each of these factors is assigned a numerical value. Mitchell and Bubenzer (in Chapter 2 of Kirkby and Morgan, 1980) discuss the application of the USLE using metric units.

3.5 MUSLE Method

The Modified Universal Soil Loss Equation (MUSLE) was developed by Williams (1975), and Williams and Berndt (1976) to predict erosion from a single storm event. Williams modified 'R' in the USLE to be a storm runoff energy factor. The value of Williams' modified *R* represents the product of runoff volume and peak discharge for an event, and is given by:

$$R_m = a + (V * Q)^b \tag{3.2}$$

where: R_m = Williams' modified *R* factor
V = the storm event runoff volume
Q = the storm event peak discharge
a and b = empirical constants

Williams and Berndt (1972) used data from experimental watersheds from 3 acres to 7 mi^2 in size to estimate a = 95 and b = 0.56 (for V and Q in English units). These values are widely used. Typical accuracy of the MUSLE is shown in Figure 3.2 from Williams (1975). The spread in the data is typical of most predictive procedures and can be even larger depending on basin complexity and significance of episodic processes. Williams' MUSLE Method is simple to use; however, like the other methods described here, it does not predict a time distribution (sedigraph) or a size distribution of sediment. Mass wasting, gullying, floodplain erosion and channel erosion processes are also not considered.

3.6 RUSLE Method

The Revised Universal Soil Loss Equation (RUSLE) was developed by Weltz et al. (1987) to extend and update the USLE for non-agricultural applications, and to incorporate data collected in a variety of geographic areas since the development of the USLE.

Various improvements are incorporated into the calculation of the equation factors, but the form of the equation remains that of the USLE. Revisions include new methods for estimating *R* in the western United States, adjustments for splash erosion on flat slopes, development of a seasonally variable *K* term, a subfactor method for calculating *C*, new *LS* calculation methods based on rill/interrill erosion ratio, and new methods for calculating *P*.

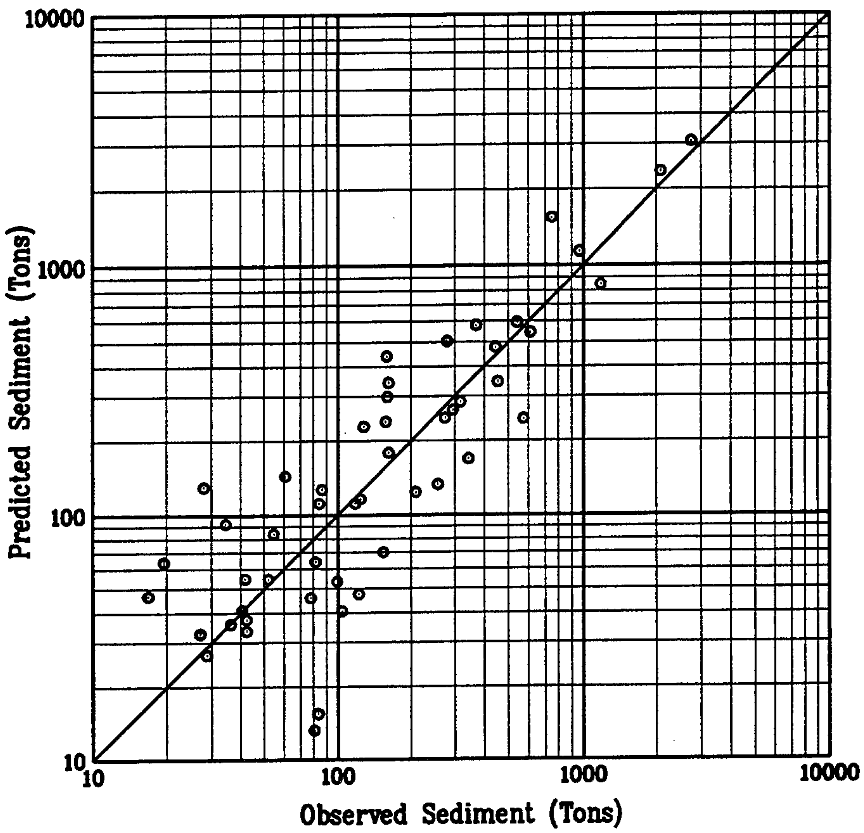


Figure 3.2 – Comparison of Observed and Predicted Sediment Yields for Watersheds W–3 and W–5 (From Williams, 1975)

50002.3_2.1.1

Readers should refer to Chapter 8 in Haan et al. (1994) for further information on the limitations and application of RUSLE.

3.7 PSIAC Method

The Pacific Southwest Interagency Committee Method (PSIAC, 1968) provides a guide for estimating yields from a watershed rating procedure based on climatic and physical characteristics. The method is intended primarily for planning purposes and results in a range of expected annual sediment yield values. The procedure was developed for basins in the western United States and is typically applicable for areas greater than 30 km^2 (10 mi^2); however, it has been successfully applied to smaller basins.

Nine factors are used to account for land use, channel erosion and transport, runoff, geology, topography, upland erosion, soils, ground cover, and climate. The PSIAC technique has compared well with actual watershed data (Shown, 1970, and Renard, 1980). Unlike the USLE and its variations, the PSIAC method estimates total annual sediment yield, rather than sheet and rill erosion. The method can be used to estimate changes in sediment yield due to land use changes.

3.8 Aerial Photography and Topographic Surveys

Comparison of sets of historical photos and surveys to present watershed conditions can often provide a means to estimate special types of sediment production such as gullying, channel bank erosion, and mass wasting. It is important to separate and quantify slow accretionary processes from more rapid and episodic avulsionary processes. Channel cross sections are necessary to make accurate estimates of bed degradation or aggradation.

Where historical aerials are not available, current aerial photography may still provide valuable supportive information such as length of eroding banks, extent of gullying, or extent and location of mass wasting processes.

Sequences of aerial photographs can be used to estimate channel bank or gully erosion by measuring aerial differences between sets of photos and computing volume based on average bank heights from field reconnaissance. Aerial photographs may also be useful in estimating bank erosion losses for single hydrologic events or longer term erosion and bank migration rates, if photos are available for periods before and after comparable historical events. Examination of historical aerial photographs is recommended for all levels of sedimentation investigations. Sediment production rates and volumes estimated from examining historical photographs can be compared to values obtained from empirical estimation formulas discussed above.

3.9 Gully Erosion Estimates

Estimates of gully erosion are best developed from field surveys, examination of historical cross section data or the examination of detailed aerial photographs if they are

available. If no data are available, gully erosion estimates can be made using an equation developed by Thompson (1964) or the procedure outlined in Technical Release 32 (SCS, 1966). Both are empirical methods that estimate gully head advancement based on drainage area and rainfall parameters. In both cases, the average depth and width of gullies must be estimated to compute the volume for a single gully, and this value must be multiplied by the number of gullies in the watershed to estimate total gully erosion.

These methods have obvious limitations in accuracy, but may be effectively used in concert with aerial photography and field reconnaissance and geomorphic assessments. Where gullying is a significant fraction of total sediment production, more detailed field measurements may be necessary. Consultation with the local SCS is advised.

3.10 Regional Analysis

Regional sediment yield analyses have been conducted for some areas of the United States. As shown in Figure 3.1, these methods are recommended as a check on other computations rather than as primary computation methods. They are also useful in providing quick preliminary estimates of yield. Discussions of several of the more widely applied regional methods are presented in Chapter 3 and Appendix C of the EM 1110-2-4000 (USACE, 1989).

Dendy and Bolton (1976) developed two regression equations relating unit sediment yield to drainage area and mean annual runoff based on sedimentation data from about 800 reservoirs throughout the continental United States. Strand and Pemberton (1982) developed a similar regional relationship for use in the semi-arid areas of the United States. The Soil Conservation Service (SCS, 1974) has developed a map of generalized sediment yield rates for the Western United States. Tatum (1963) proposed a method for computing sediment yield and debris volumes from arid, brush-covered mountainous areas in Southern California. Calculations are made from nomographs using an equation with adjustment factors for size, shape and slope of the drainage area, 3-hour precipitation, the portion of the area that may have burned and the years since the last burn and flood. Refer to Appendix C of EM 1110-2-4000 (USACE, 1989). All of these regional relationships are useful in providing general estimates for relatively large areas for the purpose of establishing a range of reasonable values. However, they should be used with caution for specific sites, especially where watershed conditions are unique or extreme.

3.11 Effects of Disturbance

Watershed sediment production, transport and yield are influenced by a complex set of geomorphic processes that are spatially and temporally dynamic. As a completely integrated system, the watershed sediment and water flow budgets represent a complex balance of forces. Once disturbed, erosion forces can outweigh erosion resistant and stabilizing forces resulting in dramatic increases in sediment production and yield. Typical events and activities that most often lead to increases in sediment yield include logging, mining, clearing and cultivation for agriculture, grazing, road construction, clearing and grading associated with urbanization, brush and forest fires, and extreme drought followed by extreme runoff events.

The effects of urbanization can lead to a number of sediment problems. Urbanization usually involves site preparation, grading, and excavation activities. Accelerated soil loss in the project area with sediment deposition in downstream flood control channels is common during construction. Therefore, during the construction phase of urbanization projects, the soil surface is typically exposed and disturbed leading to measurable increases in erosion and sediment production. Once constructed, paved and landscaped, however, sediment production from an urbanized area may drop below its original undisturbed amount, especially in basins utilizing concrete-lined drainage channels and local storm water detention ponds or debris basins.

3.12 Adjustment for Transport Capacity

Usually, a part of the soil eroded in a watershed is temporarily or permanently stored so that sediment yield out of a catchment is less than the amount of sediment production. The ratio of yield to gross production (erosion) is called the sediment delivery ratio (SDR). SDR is a dimensionless number less than or equal to one. The gross erosion and sediment delivery ratio method for estimating sediment yield is a two-step procedure. First the gross erosion (sediment production) in a catchment of given area is computed. Gross erosion includes interill, rill, gully and stream erosion. Then a sediment delivery ratio is estimated from empirical curves available in the literature (Kirkby and Morgan, 1980, and Barfield et al., 1981). Sediment yield from the catchment is obtained from the product of gross erosion and SDR.

Typically, specific sediment yield is observed to decease with increasing area. There are a few locations in the world, however, where yield is observed to increase with area. This anomalous condition has been observed in the Middle Yellow River Basin in China (Vanoni, 1975), where fine loessol soils are easily eroded and carried by runoff of even low intensity. There is greater production in the lower watershed with little loss resulting in an increase in specific yield and delivery ratio with area. The same anomalous condition has been reported for catchments in Canada and North America comprised of fine glacial materials. Urbanized catchments that are highly channelized with very efficient concrete lined drainage channels also tend to have higher sediment delivery ratios.

Sediment delivery ratio equations have been developed from studies of watersheds in particular regions, but have limited applicability elsewhere. Reservoir sedimentation data may be useful in estimating SDRs for watersheds with similar hydrologic and geomorphic characteristics to the study watershed. Sediment delivery ratio adjustments must normally be applied to methods where sheet and rill erosion are estimated using USLE or RUSLE.

Measured flow sediment data may be utilized to check the accuracy of sediment yields computed, based on erosion sources (see Section 3.13). Even where data are limited, an estimate of yield from flow and suspended sediment concentration data can assist in establishing reasonable bounds. For single event analyses, computed results should be checked against practical limits for maximum suspended sediment concentration. Where a maximum expected suspended sediment concentration can be selected, maximum yield can be calculated as:

$$Y_s max = Cmax\ V \qquad (3.3)$$

where:

$Y_s max$ is the maximum sediment yield (mass),
Cmax is the maximum expected concentration (mass/volume)
and V is the volume of clear water runoff (volume)

3.13 Use of Measured Flow and Sediment Load Data

Rigorous determination of sediment yield requires that field data be utilized for hydrologic, hydraulic, and sediment characteristics of the study area. The empirical methods described above should only be relied upon to establish trends or make reasonable estimates of expected ranges of yields. Unfortunately, detailed historical water and sediment discharge data are seldom available, and collection of data is often beyond the budgetary limitations of investigations. Limited data, in conjunction with empirical or regional analysis, will significantly improve the accuracy of estimates. A good discussion of estimating sediment yield based on field measurements, is provided in EM 1110-2-4000 (USACE, 1989). Direct measurements are divided into categories of in-stream sampling and reservoir sedimentation investigations.

In-stream sampling is the most reliable approach for determining sediment yield, provided sufficient data are available over a suitable time period and range of hydrologic conditions. Where available, long-term sediment gage records provide a reliable means of calculating yield. It is the measured suspended sediment load that is usually reported. Therefore, an adjustment must be made to account for larger materials moving as bed load, and sediment moving within about 0.2m of the bed. Field sampling methods are discussed in Guy and Norman (1976), Vanoni (1975), and USGS (1978). The unmeasured portion of the load is usually between 5 and 15 percent of the measured load, and can be estimated by empirical techniques (Colby, 1957). Adjusted long-term sediment discharge records can be used directly to estimate average annual yield and single event yield. However, adjustments may be necessary to account for watershed changes and hydrologic variation.

One of the most common methods used to estimate average annual yield is the flow-duration sediment-discharge rating curve method. The flow duration curve is integrated with the sediment discharge rating curve at the basin outflow point. This procedure can be easily utilized to predict changes in sediment yield due to changes in hydrologic regime via the flow duration curve or due to changes in watershed sediment production via the sediment-discharge rating curve. The sediment-discharge rating curve can also be modified to account for only those particles within a specific size range (e.g., sand and gravel). Unfortunately, the sediment-discharge rating curve is very difficult to develop without extensive flow and measured sediment load data. Sediment-discharge rating curves are not linear and often display looped curve characteristics making them very difficult to estimate without measured data from the basin being studied. The general flow-duration sediment-discharge curve procedure is illustrated in Figure 3.3. A detailed discussion of this computational technique is provided in EM 1110-2-4000 (USACE, 1989). The manual also provides a number of cautions regarding use of the method, and provides guidance on appropriate methods for analysis of data.

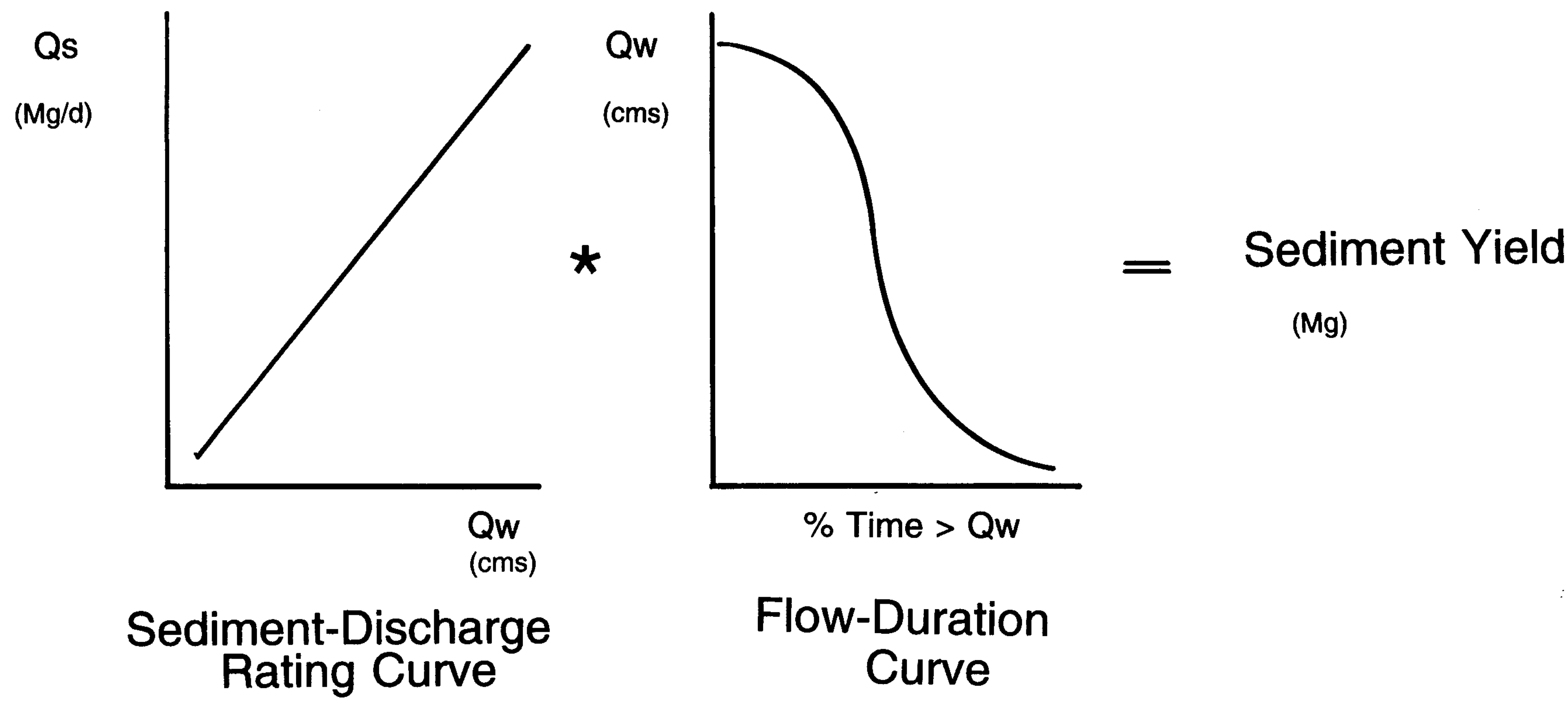


Figure 3.3 Illustration of Procedure to Estimate Sediment Yield from the Flow-Duration and Sediment-Discharge Curves.

3.14 Reservoir Sedimentation Data

Several regional sediment yield equations are based on relationships derived from reservoir sedimentation measurements (e.g., Tatum, 1963, Dendy and Bolton, 1976, and Strand and Pemberton, 1982). In some cases, reservoir sedimentation data may be available within the study watershed or in an adjacent watershed with similar characteristics. Care should be taken to ensure that soils, topography, precipitation, land use, agricultural development, and other basic characteristics are similar enough to warrant transfer of data from one watershed or region to another.

For areas east of the Rocky Mountains, the USDA (1978) has a developed procedure for transferring data. Specific sediment yield is adjusted for basin size according to the following guidelines, where A_e = area of the basin for which yield will be estimated and A_m = area of the basin for which measured data exists:

for $0.5 < A_e / A_m < 2.0$ — direct transfer

for $A_e / A_m < 0.1$ or $A_e / A_m > 10.0$ — no transfer

for other ratios of A_e / A_m — $$Y_e = Y_m (A_e / A_m)^{0.8} \quad (3.4)$$

where: Y_e = the total annual estimated yield in the unmeasured basin
and Y_m = the total annual measured yield at the reservoir site.

These guidelines do not apply to mountainous areas or other watersheds which, based on dominant geomorphic processes, would not be expected to exhibit a relatively smooth relationship between specific sediment yield and drainage area. Examples of these types of areas are sites where significant deposition may occur upstream of the estimate point, or where channel bank erosion contributes significantly to sediment yield in the lower portions of a watershed.

As with other methods, accuracy in transfer of reservoir data is limited by variability between watersheds, but is often useful in establishing reasonable bounds for estimates. Investigators should utilize all available data and compare results from as many different estimating procedures as possible. Comparison of results from regional procedures, yield maps, reservoir measurements and empirical formulas should establish reasonable bounds for yield (MacArthur et al., 1990).

3.15 Transfer of In-Stream Data

In-stream sampling data from various points in a study watershed may be integrated to give annual yield. This procedure will normally result in a relationship between annual yield and drainage area which may be extrapolated to other points in the basin. In the case where considerable scatter in the plotted yield vs. drainage area plots are evident, investigators should look for geomorphic factors that could influence the data and attempt to isolate those factors. These techniques, plus limited in-stream sampling at the estimate point, may provide a reasonable basis for both annual yield and single event estimates.

Transfer of in-stream data between watersheds can be attempted using a procedure similar to that described in Section 3.14, but with low expected accuracy. Cautions relating to watershed characteristics similar to those for transfer of reservoir sedimentation data should be applied. Data should be transferred only for annual sediment yield and not for single event measurements.

3.16 Temporal and Spatial Variability

Regardless of the analyses used or the watershed type, it is essential that temporal and spatial variability of sediment yield be considered in making estimates. These considerations should be based on watershed reconnaissance, and a basic understanding of basin geomorphology. The following hypothetical examples illustrate the need for thoughtful application of estimates based on variability.

1) In-stream sampling in a mountain gorge is used to calculate average annual and event-based sediment yields for a small stream. Just downstream of the gorge, the stream becomes braided as the gradient decreases on an alluvial fan. Sediment yield estimates based on upstream measurements, will likely be significantly in error below the alluvial fan for specific events due to temporary storage of sediments at low flow, and the potential for avulsive changes in channel location during extreme flows.

2) Reservoir sedimentation data from the past 50 years are used to estimate sediment yield for a new reservoir in a forested watershed. More careful examination of historical land use patterns would reveal that grazing was initiated in the last 10 years, and that urban development is expected to increase by 100% over the next 10 years. A long-term estimate of sediment storage volume for a reservoir might be significantly in error.

3) An empirical method is used to estimate average annual sediment yield for a chaparral watershed. The following years, a fire occurs in the watershed which increases sediment yield by a factor of 8. Analysis of historical data might indicate that the watershed could experience a fire on the average of once every 50 years, thus significantly affecting 'average' annual sediment yield, and drastically affecting yield from individual events.

These examples are intended only to illustrate the potential for temporal and spatial variability in watershed yield estimates, and not to typify specific design conditions. Each watershed will have a unique set of characteristics which vary in space and time, and the investigator must apply engineering judgement to arrive at a reasonable estimate.

3.17 Comparison and Engineering Judgement

Although the state of the science in computer modeling of erosion and sediment transport processes continues to advance, variability between watersheds is extremely high, and data requirements for calibration are often out of reach. Therefore, methods with recognized limitations in accuracy are often adopted. As outlined in Figure 3.1, one of the

most important elements in making reasonable estimates of sediment yield is utilization of several methods or techniques based on as much measured information as one can find, and comparison of all the results. This approach is essential where in-stream data is limited or lacking.

In any sediment yield estimate, engineering judgement will play a part in screening data and selecting computational factors. In addition, judgement must often be applied to account for temporal and spatial variability in the watershed characteristics which affect sediment yield. Judgement must also applied to account for the effects of watershed disturbances or the coincidence of hydrologic events with other events or processes (e.g., fire, landslides, channel avulsion) which significantly effect sediment production and yield. Investigators should always visit the project area, review the areas upstream and downstream from the project site and examine as much of the drainage basin above the site as possible. If possible, it is advisable to make an aerial reconnaissance of the basin prior to making yield estimates so that otherwise unnoticeable basin geomorphic or land use characteristics might be observed. Investigators should consider the historical and geomorphic evolution of the basin and determine whether the system is reasonably stable or adjusting to an imbalance of forces or past activities.

Chapter 4

Estimating Basin Sediment Yield and Total Inflowing Load Characteristics

4.1 Background

Sediment transport computer models for streams and reservoirs require the specification of the inflowing sediment load as an upstream boundary condition. For models such as HEC-6 it is necessary not only to know total inflowing sediment load for a range of discharges (the sediment-discharge rating curve), but also to subdivide the load into various grain size classes. Obviously, it is most desirable to obtain measured sediment load and gradation data for various flow conditions, and to base model input on measured data. However, these data are frequently unavailable or incomplete. This chapter describes the steps required to develop the total inflowing sediment load and gradation assuming little measured data are available for the study site.

4.2 General Procedures

The first step is to acquire relevant background information for the subject watershed including basin geomorphology, soil characteristics, dominant erosion and transport processes, descriptions of historical events and past floods. Measured flow and sediment load data are often not available for the study site, but may be available for adjacent basins and watersheds. Available data and reports should be obtained and carefully examined. It is also beneficial to contact people who actually collected and prepared that data to discuss what they saw, and any difficulties, shortcomings or limitations in the data. Occasionally, the data may be of the quality that it can be transposed to the study area for use in calibrating or circumstantiating the basin yield and total load relationships. Effort spent early in a study to establish what sediment production and yields are reasonable or not reasonable for various flood magnitudes, is critical to the rest of the investigation.

Prior to adopting a method for calculating sediment yield, it is very important to conduct a field reconnaissance of the project site and of the general watershed area upstream from the site. It is important to determine whether significant portions of the annual yield are coming from individual localized mechanisms such as gullying, bank caving or mass wasting. Has the basin been burned, clear cut, over-grazed or altered by other disturbances that can affect sediment production? The field reconnaissance allows the engineer to determine the main source of sediment entering the project. It is very beneficial to involve an experienced fluvial geomorphologist in the initial field reconnaissance studies. From that inspection and a review of available data for the basin, the most appropriate method or methods for estimating sediment yield and grain size distributions can be selected. If *sedimentation is critical* to the recommended project alternative, *a rigorous sediment yield analysis is recommended early in the project planning process.*

Once the initial data review and field reconnaissance are accomplished, procedures outlined herein and in Chapter 3 of Engineering Manual 1110-2-4000 (USACE, 1989) can be applied to estimate basin yield. The following outline can be used for general study purposes. Because every basin and river system is unique, specific study procedures may require adjustment and refinement to accomplish the objectives of the investigation. The procedures presented herein are discussed in more detail and illustrated with an example problem in Chapter 6.

4.3 General Steps for Estimating Sediment Yield

Potential methods for estimating sediment yield in ungaged catchments include: (1) application of regression equations based on detailed basin characteristics like rainfall intensities, soil properties, ground cover, etc., (2) use of regional relationships based on global basin characteristics like drainage area, altitude and slope-aspect ratio; (3) transposition of data from similar basins where reliable data are available; (4) integration of annual or single event yields from stream sediment rating curves and flow-duration curves or hydrographs; and (5) application of empirical methods described in Chapter 3. Any estimate should account for: (1) sheet, rill and interrill erosion from upland land surfaces; (2) gully erosion, stream bed and bank erosion; and (3) mass wasting processes in the basin. The following general steps are necessary to estimate basin sediment yield. Several of these steps may require iterative applications and adjustment in order to develop reasonable estimates.

(1) Perform field inspection and review of available data. Discuss observations and results from previous studies with local SCS field office, USGS field survey people, County flood control and channel maintenance personnel, and Corps of Engineers hydrology and hydraulics personnel.

(2) If little or no data are available, prepare a field sampling program to at least collect several bed material and bank material samples from sediment source areas and stream channel locations upstream and through the study area. Perform standard sieve analyses and settling tests on the samples.

(3) Examine published long-term daily discharge records and sediment gage records. The standard procedure used by the USGS is to plot the daily water discharge hydrograph and the daily sediment concentration graph, then integrate them as prescribed by Porterfield (1972). Results from this exercise are expressed in t/day. Before comparing sediment yields, the period-of-record data should be examined for homogeneity. Adjustments for upstream reservoirs, hydrologic record, land use changes, and farming practices may be necessary before the correlation between sediment yield and water yield can be established.

(4) Develop the daily water discharge - suspended sediment load rating curve from gage data. Integrate the flow duration curve with the measured sediment load - discharge rating curve to develop a good representation of the process-based average annual yield. (Details of how to prepare these curves and compute these values are summarized in Section 3-6 in EM 1110-2-4000 (USACE, 1989).

(5) When no field measurements exist, and at least some are required to make dependable sediment yield estimates, a limited sediment sampling program is highly recommended early in the planning phases of the study. This level of short duration sampling is often referred to as "flood water sampling." Caution is necessary, however, because the short record data set will not necessarily provide a representative sample of watershed processes for the full range of possible hydrologic conditions. Therefore, these data are less dependable than the flow duration sediment discharge rating technique. The lack of large flood data may bias the yield results.

(6) Apply several regional analysis procedures (Tatum, 1963, Dendy and Bolton, 1976, and PSIAC, 1968) to estimate average annual yield. Compare the results to published information or reports obtained from other studies in the area. Compare the yields by plotting yield vs. effective drainage area. Figure 3.1 summarizes a generalized yield estimating procedure. Attempt to establish upper and lower bounds on the yield - drainage area curve for low, average and high sediment production years (MacArthur et al., 1990). Use this range of yield values during the sediment load sensitivity studies.

(7) Use one or more yield estimating equations to estimate the average annual and single event sediment yields for a range of events (e.g., USLE, RUSLE, PSIAC, MUSLE).

(8) Multiply your gross sediment yields by an appropriate sediment delivery ratio (SDR) if necessary to give the net sediment yield at the project location. For more information on how to estimate the sediment delivery ratio and when to apply it, please refer to Section 3-14 in EM 1110-2-4000 (USACE, 1989) and pages 293-294 in Design Hydrology and Sedimentology for Small Catchments (Haan et al., 1994).

(9) A quick method for estimating single event sediment yields involves application of several reliable "annual yield" estimating methods to establish the average annual yield first. Then, assume that an equivalent amount of sediment to the average annual yield occurs during a 2-year event. Also assume that greater single event yields can be approximated by the linear extrapolation of the annual value by multiplying the annual yield by the ratio of the peak single event water flow to the 2-year flows.

$$\text{Yield}_i = \text{Yield}_{\text{AvgAnn}} * Q_i/Q_2 \tag{4.1}$$

where Yield_i is the single event yield for an i^{th}-year storm event and Q_i is the peak water discharge for the i^{th}-year event.

This method is only recommended as a procedure for establishing rough estimates of single event yields and for cross-checking values developed by other methods.

(10) Another procedure for estimating single event and average annual yields is through the application of the MUSLE single event yield method. Use the MUSLE procedure to develop single event yield estimates for the 5-, 10-, 50-

and 100-year events. Convert the single event sediment yields to an average annual value (if applicable) by integrating the sediment yield vs. probability curve. Compare this value with observed reservoir annual yield data and/or computed annual yield values. Select the most reliable value for annual yield. (This procedure is demonstrated in the example problem discussed in Chapter 6.)

(11) Decide whether gully, stream bank erosion or mass wasting processes are active in your study basin. Determine whether your selected annual and single event estimating procedures adequately account for these processes. No generalized analytical procedures are presently available to explicitly calculate these types of sediment production for the full range of possible events. Measured data are obviously the most reliable source to use; otherwise application of empirical relationships and the careful examination of pre- and post-flood event photographs are necessary.

When time, data, and budget permit, process-based erosion and yield models can be used to develop average annual and single event yields. A review of watershed erosion models is presented in Appendix A. Application of process-based erosion and yield models is generally complex and requires detailed data collection for development of model input parameters and calibration. Application of models of this type is beyond the scope of this report.

4.4 General Steps for Estimating Sediment Discharge Curves and Grain Size Distribution Relationships for Use In Mobile Boundary Models

(1) Collect representative bed material sediment samples through the project reach (see Chapter 3, USGS, 1978). Develop grain size distribution curves for each bed and bank sample and plot the representative grain sizes (D_{50}, D_{84} and D_{10}) with distance from downstream to upstream.

(2) Develop a sediment gradation curve for the wash load using measured data or watershed soil surveys. If there are no data, apply Einstein's (1950) assumption that the largest representative size present in the wash load is approximately equivalent to the D_{10} of the bed material load. Using this assumption and soil survey data regarding the approximate percentages of sands, gravels, silts, and clays, develop an approximate grain size distribution curve for the wash load fraction of the total load. (Refer to Chapter 6 for an example of this procedure.)

(3) Estimate the fraction of the total sediment load that travels as bed material load and the fraction that travels as wash load. Two methods are presented in the example problem discussed in Chapter 6. *Method one* is the presently preferred method for use with computer program HEC-6. It involves using HEC-6 through an iterative procedure to synthesize its own inflowing bed material load and gradation from the grain size distribution curves measured in the field. Wash load is then computed as the difference of the total

sediment yield volume or weight (estimated from procedures discussed in Section 4.3) and the HEC-6 estimated bed material load. *Method 2* develops the bed material load by starting with the estimated total sediment load from the computed basin yield. The approximate percentage of bed material load to total load is estimated from information and data measured in the study area. Because there are no established rules of thumb for the ratio of bed material load to total load, one assumes a value based on field observations or measured information and checks to see if that assumption is reasonable (see step number 6). If it is not, new percentages are assumed and checked until the estimated bed material load produces reliable results. Chapter 6 presents an example application of the Method 2 procedure for estimating inflowing load and the grain size distribution of that load.

(4) Develop a composite total load gradation curve by combining the bed material gradation data and curves with the wash load gradation data and curves.

(5) Apply the Corps' SAM procedures (Thomas et al., 1992) to estimate bed form-dependent *n* values. Also utilize SAM to select the most appropriate transport function for a particular river type. Check to see if the river is capable of carrying the estimated single event sediment load using SAM or HEC-6. Determine whether the river through your study reach is "supply limited" during large events or "transport limited." If it is sediment supply limited, channel bed and bank erosion may be important. If it becomes transport limited during large events, sediment accumulation and possible channel avulsion may occur.

(6) Once the total inflowing load curve is complete and an appropriate transport function(s) is selected, use them in HEC-6 or other stream sedimentation models to determine if the estimated load and gradations are in balance with the stream hydraulics and basin yield estimates. If significant deposition or scour occurs in the first few upstream cross sections, then the inflowing load may require adjustment. Once the model performs properly and the computed HEC-6 results appear stable, compare the volumes of total load, bed material load and wash load to observed data. Make adjustments to the load, grain size distribution or transport function according to procedures outlined in the HEC-6 User's Manual, CPD-6, (HEC, 1993) and TD-13 (HEC, 1992).

(7) Perform model calibration and sensitivity studies according to guidelines provided in Chapters 3, 5 and 6 of CPD-6 (HEC, 1993) and Section 3.5 in TD-13 (HEC, 1992).

Chapter 5

Evaluation of Sediment Yield Results

5.1 General

Due to the diverse nature of Corps projects and geographic location, a standard method for estimating sediment yield is not employed throughout the Corps. Instead, individual district offices select their own procedures based on the type of project being investigated, the availability of data and the potential significance that sedimentation processes have on project performance (USACE, 1989). Consequently, a variety of procedures are used throughout the Corps, but are all related closely to one of three basic approaches for estimating sediment yield, including: (1) determining sediment yield directly from sampling and monitoring programs or from river and reservoir surveys, (2) transposition and/or extrapolation of measured data from watersheds with similar characteristics to the study area, and (3) application of empirical relationships (predictive equations) and regional equations to estimate annual or single event yields. The following sections discuss the inherent difficulties associated with developing yield estimates and offer advice for checking and evaluating estimated results.

5.2 Limitations of Sediment Estimating Procedures

Estimating basin sediment yield for average annual and single event conditions requires the application of several yield estimating procedures in order to establish a reasonable range of results. Estimation of sediment transport load curves and grain size distributions for those load relationships may also involve the application of several methods in order to check and cross-check the sensitivity and reliability of estimates. Ask for input *early* in the study from others experienced with the basin being investigated and check your estimates with measured information from the area or from similar basins to circumstantiate your results. Some general considerations and limitations to remember:

(1) The variability of sediment yield from year to year, and perhaps from decade to decade, is likely to be high. This is especially true in flashy ephemeral watersheds. In extreme events like a 100-year flood, there may be a wide range of possible yields depending on antecedent basin conditions. The occurrence or non-occurrence of infrequent intense storm events can greatly affect measured annual yield rates. Spatial variability is also likely to be high, and relatively local sources can contribute large amounts of sediment (e.g., disturbed areas or mass wasting processes). Establishment and use of long-term continuous data records are important, but even long-term data may fail to account for spatial and temporal variability in extreme events.

(2) The lack of local data affects estimation of grain sizes as well as yields. Grain size distributions of delivered sediment loads are difficult to estimate. There are no presently available direct methods for computing the grain size distribution of sediment loads estimated directly from basin yields. Direct

measurement methods are the most reliable; however, soil survey information can be used to make estimates when no measured data are available. Refer to *Field Methods for Measurement of Fluvial Sediments*, by the USGS (Guy and Norman, 1976).

(3) The geomorphic behavior of the basin during a severe (e.g., 100-year) event, particularly the response of steep unstable canyon areas and exposed channel banks is difficult to predict. It is important to attempt to establish an historical geomorphic understanding of the study basin and how it may have responded in the past during significant runoff events.

(4) Seismic activity and land surface subsidence can result in significant basin responses (plan and profile adjustments). This may greatly affect sediment production, yield and channel stability. Determine whether these processes are affecting the study area.

(5) In light of these limitations and complications, there will be uncertainty associated with sediment yield and load estimates. Therefore, always perform sensitivity tests to evaluate the impact of your assumptions and of the uncertainty in the yield, load curve, or grain size distribution estimates on the project evaluations. If halving, doubling or tripling the sediment load does not greatly affect the performance of the project being evaluated, then additional data and analysis may not be necessary.

5.3 Evaluation Procedures

When little or no measured yield data are available, it may not be possible to calibrate or verify estimated values. It therefore becomes necessary to evaluate results using a variety of checking and sensitivity procedures. The general procedures outlined in Figure 3.1 are recommended. Herein, "calibration" refers to the development of representative data and model (estimation procedure) parameters based on known or deduced prototype behavior. "Verification" involves the demonstration of the calibrated model's (or estimation procedure's) ability to simulate prototype behavior for a time record different from that used during calibration. A calibrated model (or procedure) is not necessarily a verified model (or procedure). The following partial list of suggested evaluation procedures may be useful. Many additional checks and evaluation procedures are described in EM 1110-2-4000 (USACE, 1989), EM 1110-2-1416 (USACE, 1993), CPD-6 (HEC, 1993), and TD-13 (HEC, 1992).

Evaluation procedures can be generally divided into the evaluation of data and information during the early stages of an investigation, and the evaluation of computed results. The following procedures apply to data and information:

(1) Data should be reviewed to assess its accuracy and applicability based on internal consistency, collection methods, and watershed conditions during collection.

(2) Review of the history and geomorphology of the basin is necessary to interpret trends in the data and its reliability for use under present conditions. Review of

reports and literature, field reconnaissance, and interviews with individuals who have previous field and analysis experience in the study area are essential components of the historical review. Data can also be correlated to watershed conditions using historical aerial photography.

(3) It is advisable to conduct at least limited field sampling to determine whether reported data can be duplicated or verified, and to identify changes, conditions, or sampling techniques which may significantly influence accuracy or reliability of available data.

(4) Evaluate data in a temporal context to determine whether the period of record for the data is likely to accurately depict important parameters and meet study objectives.

(5) Evaluate data needs based on study requirements. For example, river sedimentation models are likely to require less accuracy in sediment yield estimates than reservoir sedimentation studies.

(6) Establish reasonable ranges for accuracy in the data, and use these ranges in sensitivity analyses.

(7) Methods for preparing and checking sediment data for use in computer program HEC-6 are discussed in Chapters 3, 5, and 6 of CPD-6 (HEC, 1993) and in Chapters 3 through 7 of TD-13 (HEC, 1992).

The following procedures apply to the evaluation of computed results:

(1) Compare computed results to measured data, even if available data are limited.

(2) Assess the accuracy of computed results based on field observations or measurements while the fluvial transport system is active (i.e., during a significant runoff event). If possible, verify computed results with field measurements.

(3) Evaluate results from a geomorphic perspective to determine whether computed results are consistent with observed or documented geomorphic trends.

(4) Evaluate computed results developed from a number of different methods, and consider potential explanations for the differences. Differences in computed results for sediment yield are often on the order of 50 to 200 percent. Selection of values for use should be based on their potential impact on project performance.

(5) Utilize initial results to decide what types of sensitivity tests are appropriate.

(6) Compare results to data or results from previous studies, and for other basins (e.g., computed results or reservoir sedimentation surveys).

(7) Establish reasonable bounds for sediment estimates, and evaluate results against this acceptable range. If methods appear to under or over estimate acceptable values, review the approach to isolate potential weak areas, and conduct sensitivity analyses to refine the method.

(8) Present the results with an explanation of expected accuracy and limitations. Clearly document assumptions, boundary conditions, data analysis, and methodology.

Chapter 6

Practical Example

6.1 Introduction and Background

This chapter presents a detailed example of how to prepare the data and apply procedures to estimate the average annual and single event sediment yields for a watershed investigation. It also discusses methods for estimating the inflowing load and grain size distribution information required by computer program HEC-6. Additional guidance is found in Chapters 3, 5 and 6 in CPD-6 (HEC, 1993), Chapters 3 through 7 in TD-13 (HEC, 1992), and Chapters 4 and 5 in EM 1110-2-4000 (USACE, 1989).

This example is for a small mountain watershed that contributes water and sediment to an intermittent stream in the southwest. A channel flood reduction project is proposed on the lower reach of the stream. The project will include a realignment of the natural flow path and a detention basin. Both the total volume of sediment and the rate of sediment transport are of concern when analyzing the performance of this proposed project during a flood event. This example will go through the development of the total inflowing sediment load for use as a boundary condition for the stream sediment transport model, HEC-6.

This example provides a framework for addressing sediment related issues. Several methods are used to determine the range of results. Available sediment data are also used in order to confirm that the range of computed results is reasonable. The plan of study or approach suggested by this example may have to be modified in order to suit the specific conditions of a particular application.

6.2 Description of Watershed

The site is located in the southwestern U.S. and is known for moderate sediment movement along the undulating slopes and wash deposits that emanate from the adjacent mountain range. Figure 6.1 shows the geologic structure of the region. The mountain range is made up of igneous rock formations. Erosion of these parent materials has created the macrotopography into which the natural stream channel has formed.

Figure 6.2 shows a schematic diagram of the watershed. The total contributing drainage area above the project site is 8.3 km^2 (3.2 mi^2). The watershed is divided into 17 subbasins labeled A through Q. The purpose of this subdivision is to evaluate specific soil properties and the effect of certain land use changes that are expected to occur within the watershed. If this was not of concern, then subdivision of the watershed into fewer basins, or, perhaps, no subdivision would be reasonable.

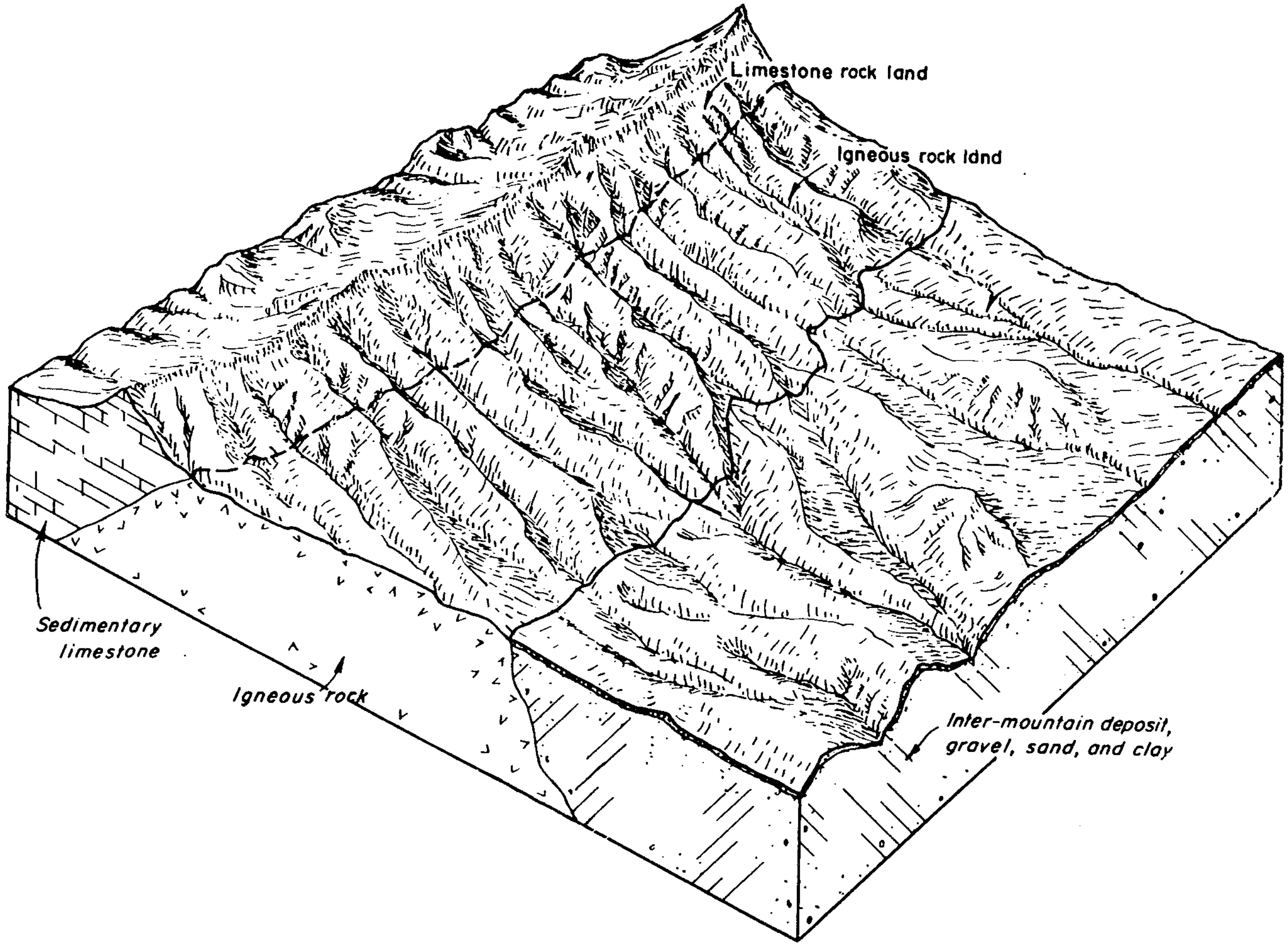


Figure 6.1
Geologic Diagram for Example Problem Study Area.

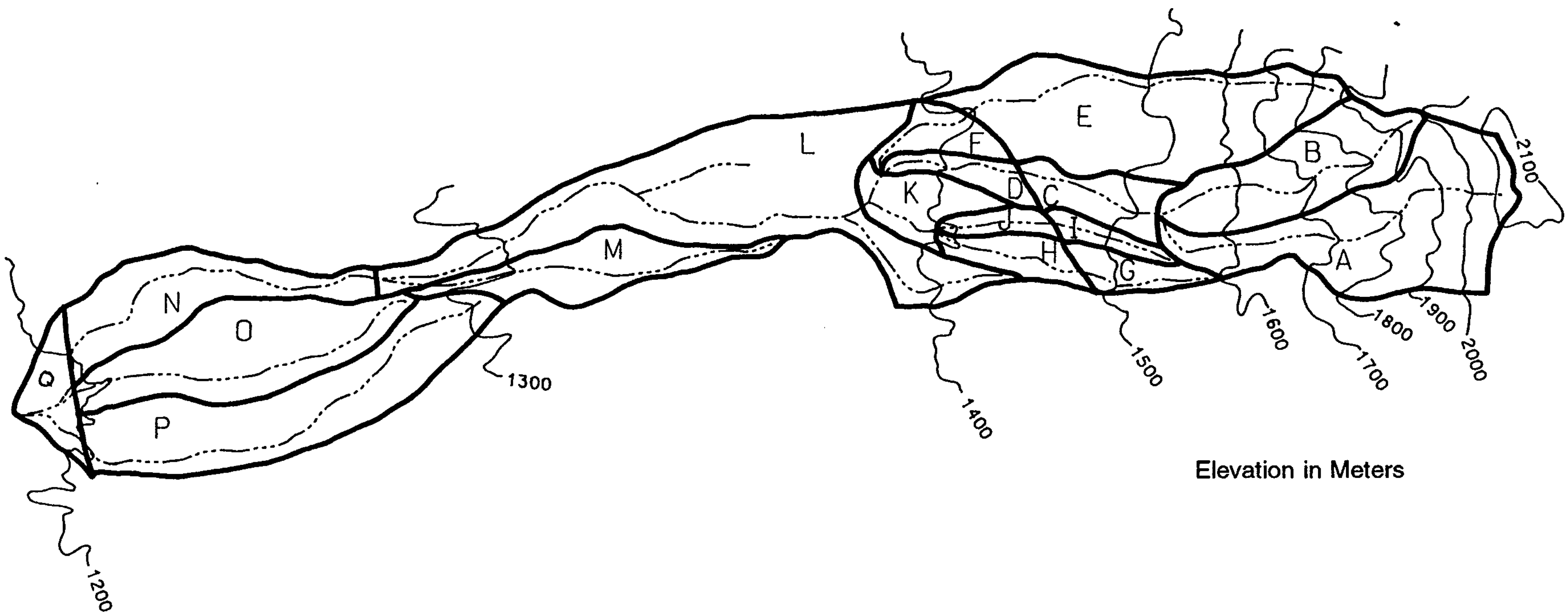


Figure 6.2
Watershed Map for Example Problem.

6.3 Watershed Sediment Yield Estimation

The first step in estimating sediment yield is to research existing sediment data. For this example, no measured sediment data are available for the watershed or for the stream. Regional data on average annual sediment yield based on reservoir surveys in other basin were available from several sources. These estimates are listed in table 6.1 below. The example problem has characteristics similar to those found in the study areas of the regional studies.

Table 6.1
Regional Sediment Yield Data

Source	Location	Sediment Yield $kg/m^2 \cdot yr$ (tons/acre·yr)
Bondurant (1951)	Conchas Reservoir New Mexico	0.022 to 0.95 (0.1 to 4.3)
SCS (1936)	Rio Grande, Pecos, and Zuni Rivers	0.066 to 0.90 (0.3 to 4.1)
USGS (1952)	Navajo Reservation	0.007 to 0.90 (0.03 to 4.1)
USGS (1982)	San Juan River	0.22 to 0.26 (1.0 to 1.2)
SCS Yield Maps (1974)	Project Region	0.044 to 0.22 (0.2 to 1.0)

In addition to reservoir sediment deposits, regional data suggest that wash load concentrations of 100,000 ppm are possible during a flood event.

Wash load is governed by the amount of sediment available from the watershed and the flashy nature of the watershed. Bed material load, on the other hand, is related to the hydraulic transport capacity of the channel. It is important to estimate the potential wash load independently because its concentration can affect the bed material transport capacity, as described by Vanoni (1953).

Several methods are used to estimate the potential sediment yield for the watershed. These methods typically fall into two categories: single event, and average annual. Most design projects require quantification of sediment transport volumes for a specific event. Most sediment yield methods, on the other hand, focus on estimating the average annual sediment yield. It is always desirable to use several methods of analysis when estimating potential sediment yields. In light of this, both the single event and average annual sediment yields are computed here. These values are then compared to measured sediment yield data. Sediment yield was also estimated from the SCS (1974) Sediment Yield Rates Maps for the Western United States. The sediment yield for the project location estimated from the SCS maps is 290 $m^3/km^2/yr$ (approximately 0.6 $acre\text{-}ft./mi^2/yr$).

6.3.1 Single Event Sediment Yield Method 1

The Modified Universal Soil Loss Equation (MUSLE) approximates the watershed sediment yield for a single event. Williams and Berndt (1972) developed the MUSLE equation to estimate the sediment yield Y_s in Mg (tons) of sediment per storm event. For SI units:

$$Y_s = 0.907 \cdot R \cdot K \cdot LS \cdot CP \qquad (6.1a)$$

For English units:

$$Y_s = R \cdot K \cdot LS \cdot CP \qquad (6.1b)$$

in which R is the runoff energy factor, K is the soil erodibility factor, LS is the length slope factor, and CP is the cover and erosion control factor. Although this equation predicts sediment yield from sheet and rill erosion, it can be used to account for other erosion processes if calibration is performed. Note that both the R and LS factors must be computed using the units specified.

Runoff Energy Factor. The runoff energy factor was calibrated using data from watersheds in Texas and Nebraska.

For SI units:

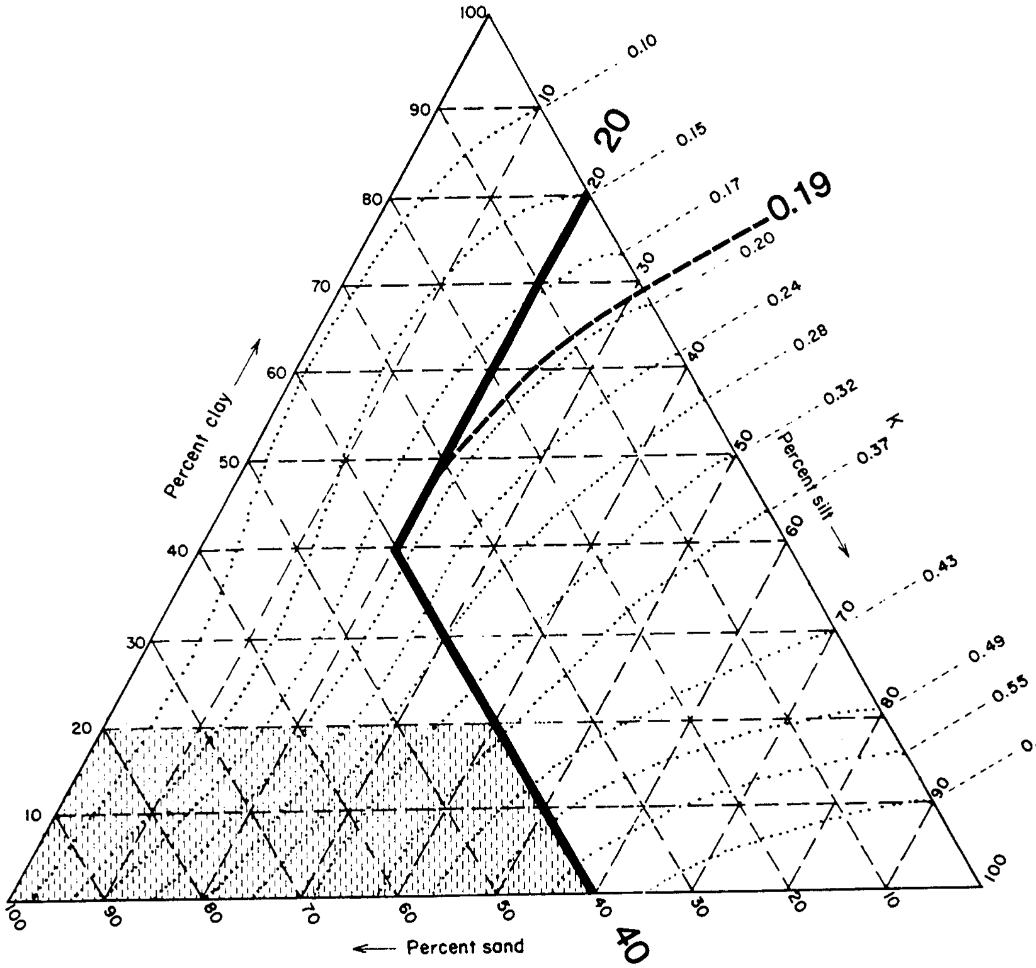
$$R = 13(Q_p V)^{0.56} \qquad (6.2a)$$

For English units:

$$R = 95(Q_p V)^{0.56} \qquad (6.2b)$$

where Q_p is the peak flow in m^3/s (ft^3/s) and V is the runoff volume in m^3 (acre-ft) for a given subbasin and for a given event. For this example the results of a rainfall runoff analysis for the 5-, 10-, 50-, and 100-year events are available to determine the runoff rate and volume from each subbasin.

Soil Erodibility Factor. The soil erodibility factor is a relative measure of the potential for soil particles to become detached by rainfall and runoff. It has traditionally been considered to be primarily a function of the soil texture. Figure 6.3 shows a nomograph used to estimate the value of K. According to a soil survey of the study area prepared by the Soil Conservation Service, the primary soil complex has the following texture: sands and gravels, 40%; Silts, 20%; and Clay, 40%. Using the nomograph gives a value of K=0.19. There are other means of determining the value of K. For example, some soil surveys include a recommended value in the data tables. Since K typically varies from 0.05 to 0.7, judgement based upon the relative erosivity of the soil can also be used. If you think the MUSLE procedure is producing too little or too much sediment, the K factor is one of the factors that can be adjusted, but only if it does not violate the assumptions the equation is based on.



Example:
Sand and Gravel Fraction: 40%
Silt Fraction: 20%
Clay Fraction: 40%

Figure 6.3
Determination of K Value Based on Soil Texture.

Always consult the local office of the SCS for advice on a reasonable range of *K* values for your particular study area.

Length Slope Factor. This factor requires an estimate of the representative length of individual overland flow surfaces in the subbasin (not the length of the subbasin), and the representative basin slope. Williams and Berndt (1976) developed a relationship for the typical overland flow length in a watershed as:

$$L_{of}=0.5\frac{A}{L_t} \tag{6.3}$$

in which L_{of} is the overland flow length in meters (feet), A is the subbasin drainage area in m^2 (ft^2), and L_t is the total length of all major channels in the subbasin in meters (feet).

The representative basin slope S is computed by the difference in the maximum and minimum elevations divided by the basin length. The length slope factor is computed from the following equation in SI units:

$$LS=\left(\frac{65.41S^2}{S^2+10{,}000}+\frac{4.56S}{\sqrt{S^2+10{,}000}}+0.065\right)\left(\frac{L_{of}}{22.1}\right)^n \tag{6.4a}$$

in English units:

$$LS=\left(\frac{65.41S^2}{S^2+10{,}000}+\frac{4.56S}{\sqrt{S^2+10{,}000}}+0.065\right)\left(\frac{L_{of}}{72.5}\right)^n \tag{6.4b}$$

where L_{of} is in meters (feet), S is in percent, and the exponent n is 0.2 for slopes less than 1%, 0.3 for slopes 1 to 3 percent, 0.4 for slopes 3 to 5 percent and 0.5 for slopes greater than 5%.

Cover Factor. The cover factor *C* was originally defined as the ratio of soil loss from land with a specified cover or plant type to the corresponding loss from bare soil. Wischmeier (1972) discusses a method to determine *C* based on vegetative canopy height, contact vegetation density, and root network. For this example problem the following reasoning is used. It was generally known by local practicing engineers, that erosion rates increased by 4 to 6 times if native vegetation is removed from the soil. This would indicate that the value of C should be between 0.15 and 0.25; therefore value of C=0.20 is chosen for the example.

Erosion Control Factor. The erosion control practice factor P, by definition is the ratio of soil loss from any conservation support practice to that with up- and downslope tillage. It is used to evaluate the effects of contour tillage, stripcropping, terracing, subsurface drainage and dry-land farm surface roughening. The P factor is typically used only for agricultural lands and rangelands where conservation support practices are being applied. Chapter 8 in Haan, et al, (1994) provides more discussion on where and how to use the erosion control factor for soil conservation studies.

For baseline conditions with no active conservation support practices, the P factor is typically 1.0. This example covers only the baseline alternative for which P=1.0

Computation of Sediment Yield Using MUSLE. The Sediment yield for each event is computed by multiplying each of the individual factors in Equation 6.1 together. The values of 100-year peak flow and runoff volume for each subbasin are taken from results from a previous hydrologic analysis. For other frequency events the following ratios of the *n*-year event to the 100-year event are used, 5-year: 0.42, 10-year: 0.50, and 50-year: 0.85. If the data are available, it is also possible to use the individual n^{th}-year peak flow and runoff volume to compute individual n^{th}-year single event sediment yields using MUSLE. This individual event computation procedure is often preferred over the application of the simple rationing methods mentioned earlier. Because the required hydrologic data were not available for this example, the simplified method was used.

Check That You Do Not Exceed the Limiting Concentration. Even though wash load is seldom controlled by transport capacity, evidence for this example indicates that 650,000 ppm by weight is the maximum possible wash load concentration. This value is close to the physical limit for sediment concentrations and is unlikely to ever occur. For most of the Western U.S., a much lower value of maximum expected wash load concentration would be appropriate (perhaps 100,000 ppm; again, check with the local SCS for advice). The purpose of considering the limiting concentration is to check the reasonableness of computed sediment yield values. This can be done by using the following equation:

$$Y_{sMAX} = \left(\frac{650,000}{1,000,000}\right) (\gamma_w V) \qquad (6.5)$$

where:

Y_{sMAX} = maximum sediment yield in kilograms (pounds) based on a limiting concentration you select (in this example it is 650,000 ppm).
γ_w = unit weight of water (1,000 kg/m^3 or 62.4 lb/ft^3).
V = clear water runoff volume in m^3 (ft^3).

Tables 6.2, 6.3, 6.4, and 6.5 show the sediment yield for the 5-, 10-, 50-, and 100-year events. Note that the computed sediment yield is compared to the yield based on limiting concentration and only the lesser of the two is used in subsequent calculations.

Summarize MUSLE Results. A review of Tables 6.2 through 6.5 indicates that the computed sediment yields using the MUSLE equation do not exceed the assumed limiting concentrations. For the entire watershed, the overall sediment concentration by volume is approximately 6.8%. Table 6.6 summarizes the sediment yield estimates in metric and English tons per event from this analysis.

Table 6.2

Summary of Sediment Yield Computations for the 5-Year Event

Sub-Basin Name	Computed 100-Year Volume (m^3)	Computed 100-Year Peak Flow (m^3/s)	Reduction for n-Year Event	R Value	K Value	Main Channel Length L (m)	Difference in Elevation (m)	Basin Slope (%)	Total Length of Channels Lt (m)	Drainage Area (km^2)	Overland Flow Length (m)	Exponent for LS Equation	LS Value	CP Value	Computed Sediment Yield Ys (Mg)	Maximum Yield Based on Cw=0.65 (Mg)
A	45,640	19.1	0.42	10,442	0.19	2,195	680	31.0	3,200	0.868	136	0.5	17.71	0.2	6,373	29,666
B	25,904	12.5	0.42	6,007	0.19	1,676	488	29.1	1,981	0.497	125	0.5	15.35	0.2	3,178	16,837
C	9,868	5.5	0.42	2,203	0.19	823	110	13.3	823	0.184	112	0.5	4.07	0.2	309	6,414
D	6,168	3.6	0.42	1,330	0.19	914	61	6.7	914	0.119	65	0.5	1.13	0.2	52	4,009
E	48,107	20.9	0.42	11,314	0.19	2,286	524	22.9	3,353	0.919	137	0.5	10.84	0.2	4,228	31,269
F	7,401	4.1	0.42	1,600	0.19	914	24	2.7	914	0.137	75	0.3	0.34	0.2	19	4,811
G	6,168	4.3	0.42	1,472	0.19	701	121	17.2	701	0.124	89	0.5	5.45	0.2	277	4,009
H	7,401	4.1	0.42	1,600	0.19	914	79	8.7	914	0.137	75	0.5	1.74	0.2	96	4,811
I	3,701	2.3	0.42	785	0.19	671	98	14.5	671	0.070	52	0.5	3.19	0.2	86	2,405
J	3,701	2.5	0.42	817	0.19	671	64	9.5	671	0.075	56	0.5	1.73	0.2	49	2,405
K	9,868	5.7	0.42	2,241	0.19	823	82	10.0	1,219	0.189	78	0.5	2.18	0.2	169	6,414
L	45,640	16.0	0.42	9,462	0.19	3,962	177	4.5	5,486	1.106	101	0.4	0.73	0.2	238	29,666
M	19,736	8.9	0.42	4,261	0.19	2,438	91	3.7	2,743	0.469	85	0.4	0.56	0.2	83	12,828
N	27,137	13.3	0.42	6,358	0.19	2,286	73	3.2	2,926	0.663	113	0.4	0.53	0.2	117	17,639
O	30,838	14.5	0.42	7,174	0.19	2,134	94	4.4	2,591	0.743	143	0.4	0.83	0.2	206	20,044
P	39,472	17.5	0.42	9,171	0.19	2,743	104	3.8	3,353	0.956	143	0.4	0.70	0.2	220	25,657
Q	11,102	6.4	0.42	2,557	0.19	1,219	37	3.0	1,219	0.262	107	0.4	0.49	0.2	43	7,216

Total Sediment (Mg)=	15,743
Total Water (m^3)=	146,096
Sediment Unit Weight (kg/m^3)=	1,760
Average Cv=	0.061

Table 6.3

Summary of Sediment Yield Computations for the 10-Year Event

Sub-Basin Name	Computed 100-Year Volume (m^3)	Computed 100-Year Peak Flow (m^3/s)	Reduction for n-Year Event	R Value	K Value	Main Channel Length L (m)	Difference in Elevation (m)	Basin Slope (%)	Total Length of Channels Lt (m)	Drainage Area (km^2)	Overland Flow Length (m)	Exponent for LS Equation	LS Value	CP Value	Computed Sediment Yield Ys (Mg)	Maximum Yield Based on Cw=0.65 (Mg)
A	45,640	19.1	0.50	12,694	0.19	2,195	680	31.0	3,200	0.868	136	0.5	17.71	0.2	7,747	29,666
B	25,904	12.5	0.50	7,302	0.19	1,676	488	29.1	1,981	0.497	125	0.5	15.35	0.2	3,864	16,837
C	9,868	5.5	0.50	2,679	0.19	823	110	13.3	823	0.184	112	0.5	4.07	0.2	376	6,414
D	6,168	3.6	0.50	1,617	0.19	914	61	6.7	914	0.119	65	0.5	1.13	0.2	63	4,009
E	48,107	20.9	0.50	13,754	0.19	2,286	524	22.9	3,353	0.919	137	0.5	10.84	0.2	5,140	31,269
F	7,401	4.1	0.50	1,944	0.19	914	24	2.7	914	0.137	75	0.3	0.34	0.2	23	4,811
G	6,168	4.3	0.50	1,789	0.19	701	121	17.2	701	0.124	89	0.5	5.45	0.2	336	4,009
H	7,401	4.1	0.50	1,944	0.19	914	79	8.7	914	0.137	75	0.5	1.74	0.2	117	4,811
I	3,701	2.3	0.50	955	0.19	671	98	14.5	671	0.070	52	0.5	3.19	0.2	105	2,405
J	3,701	2.5	0.50	993	0.19	671	64	9.5	671	0.075	56	0.5	1.73	0.2	59	2,405
K	9,868	5.7	0.50	2,725	0.19	823	82	10.0	1,219	0.189	78	0.5	2.18	0.2	205	6,414
L	45,640	16.0	0.50	11,502	0.19	3,962	177	4.5	5,486	1.106	101	0.4	0.73	0.2	290	29,666
M	19,736	8.9	0.50	5,180	0.19	2,438	91	3.7	2,743	0.469	85	0.4	0.56	0.2	101	12,828
N	27,137	13.3	0.50	7,728	0.19	2,286	73	3.2	2,926	0.663	113	0.4	0.53	0.2	142	17,639
O	30,838	14.5	0.50	8,721	0.19	2,134	94	4.4	2,591	0.743	143	0.4	0.83	0.2	251	20,044
P	39,472	17.5	0.50	11,149	0.19	2,743	104	3.8	3,353	0.956	143	0.4	0.70	0.2	268	25,657
Q	11,102	6.4	0.50	3,109	0.19	1,219	37	3.0	1,219	0.262	107	0.4	0.49	0.2	53	7,216
													Total Sediment (Mg)=		19,138	
													Total Water (m^3)=		173,924	
													Sediment Unit Weight (kg/m^3)=		1,760	
													Average Cv=		0.063	

Table 6.4

Summary of Sediment Yield Computations for the 50-Year Event

Sub-Basin Name	Computed 100-Year Volume (m^3)	Computed 100-Year Peak Flow (m^3/s)	Reduction for n-Year Event	R Value	K Value	Main Channel Length L (m)	Difference in Elevation (m)	Basin Slope (%)	Total Length of Channels Lt (m)	Drainage Area (km^2)	Overland Flow Length (m)	Exponent for LS Equation	LS Value	CP Value	Computed Sediment Yield Ys (Mg)	Maximum Yield Based on Cw=0.65 (Mg)
A	45,640	19.1	0.85	22,999	0.19	2,195	680	31.0	3,200	0.868	136	0.5	17.71	0.2	14,037	29,666
B	25,904	12.5	0.85	13,229	0.19	1,676	488	29.1	1,981	0.497	125	0.5	15.35	0.2	7,000	16,837
C	9,868	5.5	0.85	4,853	0.19	823	110	13.3	823	0.184	112	0.5	4.07	0.2	681	6,414
D	6,168	3.6	0.85	2,929	0.19	914	61	6.7	914	0.119	65	0.5	1.13	0.2	114	4,009
E	48,107	20.9	0.85	24,920	0.19	2,286	524	22.9	3,353	0.919	137	0.5	10.84	0.2	9,312	31,269
F	7,401	4.1	0.85	3,523	0.19	914	24	2.7	914	0.137	75	0.3	0.34	0.2	41	4,811
G	6,168	4.3	0.85	3,242	0.19	701	121	17.2	701	0.124	89	0.5	5.45	0.2	609	4,009
H	7,401	4.1	0.85	3,523	0.19	914	79	8.7	914	0.137	75	0.5	1.74	0.2	212	4,811
I	3,701	2.3	0.85	1,730	0.19	671	98	14.5	671	0.070	52	0.5	3.19	0.2	190	2,405
J	3,701	2.5	0.85	1,800	0.19	671	64	9.5	671	0.075	56	0.5	1.73	0.2	108	2,405
K	9,868	5.7	0.85	4,936	0.19	823	82	10.0	1,219	0.189	78	0.5	2.18	0.2	372	6,414
L	45,640	16.0	0.85	20,839	0.19	3,962	177	4.5	5,486	1.106	101	0.4	0.73	0.2	525	29,666
M	19,736	8.9	0.85	9,386	0.19	2,438	91	3.7	2,743	0.469	85	0.4	0.56	0.2	182	12,828
N	27,137	13.3	0.85	14,002	0.19	2,286	73	3.2	2,926	0.663	113	0.4	0.53	0.2	258	17,639
O	30,838	14.5	0.85	15,800	0.19	2,134	94	4.4	2,591	0.743	143	0.4	0.83	0.2	454	20,044
P	39,472	17.5	0.85	20,199	0.19	2,743	104	3.8	3,353	0.956	143	0.4	0.70	0.2	485	25,657
Q	11,102	6.4	0.85	5,632	0.19	1,219	37	3.0	1,219	0.262	107	0.4	0.49	0.2	95	7,216
												Total Sediment (Mg)=			34,673	
												Total Water (m^3)=			295,670	
												Sediment Unit Weight (kg/m^3)=			1,760	
												Average Cv=			0.067	

Table 6.5

Summary of Sediment Yield Computations for the 100-Year Event

Sub-Basin Name	Computed 100-Year Volume (m^3)	Computed 100-Year Peak Flow (m^3/s)	Reduction for n-Year Event	R Value	K Value	Main Channel Length L (m)	Difference in Elevation (m)	Basin Slope (%)	Total Length of Channels Lt (m)	Drainage Area (km^2)	Overland Flow Length (m)	Exponent for LS Equation	LS Value	CP Value	Computed Sediment Yield Ys (Mg)	Maximum Yield Based on Cw=0.65 (Mg)
A	45,640	19.1	1.00	27,590	0.19	2,195	680	31.0	3,200	0.868	136	0.5	17.71	0.2	16,839	29,666
B	25,904	12.5	1.00	15,870	0.19	1,676	488	29.1	1,981	0.497	125	0.5	15.35	0.2	8,397	16,837
C	9,868	5.5	1.00	5,822	0.19	823	110	13.3	823	0.184	112	0.5	4.07	0.2	817	6,414
D	6,168	3.6	1.00	3,514	0.19	914	61	6.7	914	0.119	65	0.5	1.13	0.2	137	4,009
E	48,107	20.9	1.00	29,894	0.19	2,286	524	22.9	3,353	0.919	137	0.5	10.84	0.2	11,171	31,269
F	7,401	4.1	1.00	4,226	0.19	914	24	2.7	914	0.137	75	0.3	0.34	0.2	49	4,811
G	6,168	4.3	1.00	3,889	0.19	701	121	17.2	701	0.124	89	0.5	5.45	0.2	731	4,009
H	7,401	4.1	1.00	4,226	0.19	914	79	8.7	914	0.137	75	0.5	1.74	0.2	254	4,811
I	3,701	2.3	1.00	2,075	0.19	671	98	14.5	671	0.070	52	0.5	3.19	0.2	228	2,405
J	3,701	2.5	1.00	2,159	0.19	671	64	9.5	671	0.075	56	0.5	1.73	0.2	129	2,405
K	9,868	5.7	1.00	5,922	0.19	823	82	10.0	1,219	0.189	78	0.5	2.18	0.2	446	6,414
L	45,640	16.0	1.00	24,999	0.19	3,962	177	4.5	5,486	1.106	101	0.4	0.73	0.2	630	29,666
M	19,736	8.9	1.00	11,259	0.19	2,438	91	3.7	2,743	0.469	85	0.4	0.56	0.2	218	12,828
N	27,137	13.3	1.00	16,798	0.19	2,286	73	3.2	2,926	0.663	113	0.4	0.53	0.2	309	17,639
O	30,838	14.5	1.00	18,955	0.19	2,134	94	4.4	2,591	0.743	143	0.4	0.83	0.2	545	20,044
P	39,472	17.5	1.00	24,232	0.19	2,743	104	3.8	3,353	0.956	143	0.4	0.70	0.2	582	25,657
Q	11,102	6.4	1.00	6,757	0.19	1,219	37	3.0	1,219	0.262	107	0.4	0.49	0.2	114	7,216
												Total Sediment (Mg)=			41,595	
												Total Water (m^3)=			347,847	
											Sediment	Unit Weight (kg/m^3)=			1,760	
												Average Cv=			0.068	

Table 6.6
Summary of MUSLE Sediment Yield Analysis

Recurrence Interval (Years)	Sediment Yield in Mg (tons)
100	41,600 (45,850)
50	34,760 (38,300)
10	19,140 (21,090)
5	15,740 (17,345)

6.3.2 Single Event Sediment Yield Method 2

The Los Angeles District of the Corps of Engineers developed a method to estimate the amount of debris coming from a single watershed (USAED, 1992). It is based on surveyed debris basin deposits for single storm events in the southern California area. For SI units:

$$\log D_y = 0.18 \log A + 0.65 \log P + 0.62 \log RR + 1.10 \tag{6.7a}$$

For English units:

$$\log D_y = 0.18 \log A + 0.65 \log P + 0.62 \log RR + 0.36 \tag{6.7b}$$

Where D_y is the debris yield at the mouth of a single watershed in m^3/km^2 (yd^3/mi^2), A is the contributing drainage area in km^2 (acres), P is the maximum 1-hour rainfall in mm (inches x 100), and RR is the relief ratio of the watershed in m/km (ft/mi). Note that the Los Angeles District has developed other regression equations for different sized drainage areas, and also that the method has the ability to incorporate the effects of fire.

The Los Angeles District method is essentially a curve fit of measured data from a specific region. It therefore does not have the same flexibility in its application as MUSLE. In fact, because the data include sediment from discrete hillslope failure events within the watershed such as surficial soil slips, bank erosion, etc., in addition to sheet and rill erosion, its application to very small or very flat drainage areas outside of the Los Angeles basin should be avoided. In this example case, D_y is computed for the entire watershed without subdivision. Use of this procedure in this example problem is for comparison.

Using a value of A=8.3 km^2 (3.2 mi^2), P=75 mm in one hour (300 for English Units), and RR=130 m/km (700 ft/mi), the computed value of D_y=6,260 m^3/km^2 (21,390 yd^3/mi^2). By incorporating the drainage area and a typical soil unit weight of 1,760 kg/m^3 (110 lb/ft_3) the resulting sediment yield for this method is 91,520 Mg (100,870 tons).

This computed value is approximately two times larger than the 100-year event sediment yield computed using MUSLE. This is considered good agreement because the

Los Angeles District Method includes sediment produced from slope failure, bank erosion, and other sources. MUSLE includes only sheet and rill erosion. Discrete sediment sources can often make up a large percentage of the total sediment yield.

6.3.3 Average Annual Sediment Yield Method Number 1

The Pacific Southwest Interagency Committee (PSIAC, 1968) method uses a subjective rating of nine physically-based factors in order to estimate the average annual sediment yield from a watershed. The sediment yield can range from 95 to 1,430 m^3/km^2 (0.2 to 3.0 acre-ft/mi^2). The PSIAC procedure includes sediment from all sources. For the example problem, the PSIAC rating values in Table 6.7 are determined for the conditions in the example watershed, based on whether each category has a low, moderate, or high impact on affecting the sediment yield.

Table 6.7
PSIAC Method for Average Annual Sediment Yield

Category	Subjective Rating	Value
Surface Geology	High	10
Soils	Moderate	5
Climate	Moderate	5
Runoff	Moderate	5
Topography	High	20
Ground Cover	Moderate	10
Land Use	Low	-10
Upland Erosion	Moderate	10
Sediment Transport	Moderate	10
Total		**65**

Based on a total value of 65 the PSIAC method indicates that the average annual sediment yield in the example catchment ranges from 240 to 480 m^3/km^2 (0.5 to 1.0 acre-ft/mi^2). Using an upper end value of unit sediment yield, the drainage area of 8.3 km^2, and a soil unit weight of 1,760 kg/m^3 (110 lb/ft^3), the sediment yield from the example basin is approximately 7,010 Mg/yr (7,730 tons/yr).

6.3.4 Average Annual Sediment Yield Method Number 2

A second method for estimating average annual sediment yield is from the generalized sediment yield maps developed by the Soil Conservation Service (1974) for the Western United States. Examination of the yield maps for this example site produces an estimated sediment production rate of 290 $m^3/km^2 \cdot yr$ (0.6 acre-ft/mi^2·yr). The resulting sediment yield from the example watershed is 4,185 Mg/yr (4,610 tons/yr).

6.3.5 Summary of Sediment Yield Computations

In order to verify that the sediment yield computations are reasonable, it is necessary to convert both computed values and observed data to a common baseline such as Mg/yr (tons/yr) for the entire watershed. The single event values computed by MUSLE are converted into an average annual value by using the trapezoid rule to integrate the sediment yield vs. probability curve for the full range of single event yields (e.g., 5- to 100-year):

$$Y_{AVG}=0.02\,Y_{100}+0.04\,Y_{50}+0.09\,Y_{10}+0.15\,Y_{5} \tag{6.9}$$

In equation 6.9, Y_{AVG} is the average annual sediment yield in Mg/yr for the entire watershed and Y_i are the individual event sediment yields in Mg. The single event yield values from Table 6.6 are used in Equation 6.9 to produce the average annual sediment yield of approximately 6,300 Mg/yr (6,940 tons/yr). The value based upon MUSLE is within the range of annual sediment yields computed by the PSIAC method and the SCS soil maps. Recall the Los Angeles District Method gave a resulting sediment yield about two times higher than MUSLE for reasons previously stated.

The regional sediment yield data from Table 6.1 are used to check the results of the computations. An average of the five data sources indicates that the observed sediment yield ranges from 0.08 to 0.8 $kg/m^2 \cdot yr$ (0.4 to 4.0 tons/acre·yr). For the example watershed, this equates to a range of 750 to 7,500 Mg/yr (820 to 8,200 tons/yr). With the exception of the Los Angeles District method, the computations are all within the range of the measured data. Table 6.8 presents a summary of the estimated yield values developed from the various data sources and computational methods used for this example.

The self-consistency of the computed sediment yields and their general agreement with measured data augment the confidence with which these estimates can be used. Because the result of the Los Angeles District method appears to lay outside the measured data, there is reason to believe that it may overestimate the sediment yield for the reasons previously mentioned in Section 6.3.2. Results from MUSLE computations are used to develop the sediment inflow rating curve.

Readers are encouraged to use several different procedures and compare those results with the observed yield data to draw the most sound conclusions possible from the data available. After the yield is determined, the approximate grain size distribution must be estimated. The computed yield is assumed to be approximately equal to the total inflowing load.

Table 6.8
Summary of Estimate Yield Values

No.	Data Source or Computational Method	Data Type	Average Annual Yield (Mg/yr)
1	MUSLE	Computed	6,300
2	L.A. District	Computed	~ 12,000
3	PSIAC	Computed	7,010
4	SCS Maps	Est. from Regional Maps	4,185
5	References in Table 6.1	Measured Data	750 to 7,500
		Arithmetic Average	6780 Mg/yr

6.4 Sediment Gradation

This section describes procedures for estimating the grain size distribution once the total volume of sediment delivered from the watershed is estimated. Presently, there are no explicit methods for computing the grain size distribution for the bed material load or wash load fractions if all you know is the approximate total load. Estimation procedures that implement simplifying assumptions are typically applied. Results should be checked with measured data whenever possible. Field application of rainfall simulators has also been used as a method for developing the approximate sediment distributions where no measured data are available.

Typically, the grain size distribution for the wash load portion of the total load is estimated separately from the bed material load. In river hydraulic studies, it is not as important to accurately account for the wash load portion of the total load. However, in reservoir sedimentation studies, it is very important to account for the wash load.

6.4.1 Bed Material

Bed material sediment samples are collected at five locations along the example stream. Standard sieve analyses are performed. The plotted sediment gradations are shown in Figure 6.4. The gradation curves for all samples are similar, and the study reach is relatively short; therefore, for this example a composite bed material gradation curve is developed from the samples. Field reconnaissance indicates that the sieve sampling did not account for the larger cobbles and boulders that are present in the bed material. Figure 6.5 shows the representative bed material gradation that is used for the sediment transport analysis.

6.4.2 Wash Load

Einstein (1950) indicates that the maximum grain diameter of the wash load is approximately equal to the D_{10} of the representative bed material gradation. From

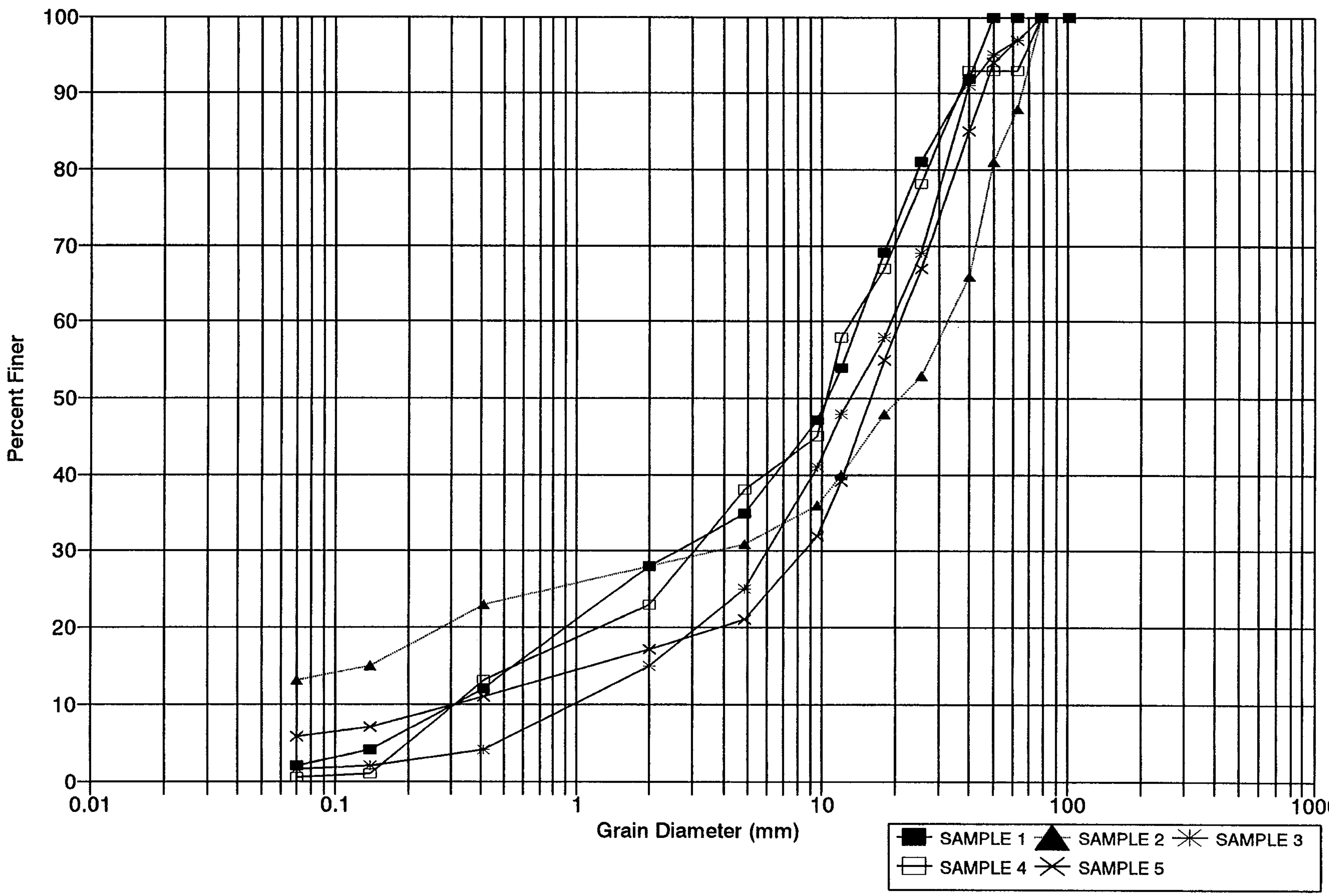


Figure 6.4
Measured Gradations for 5 Bed Material Samples

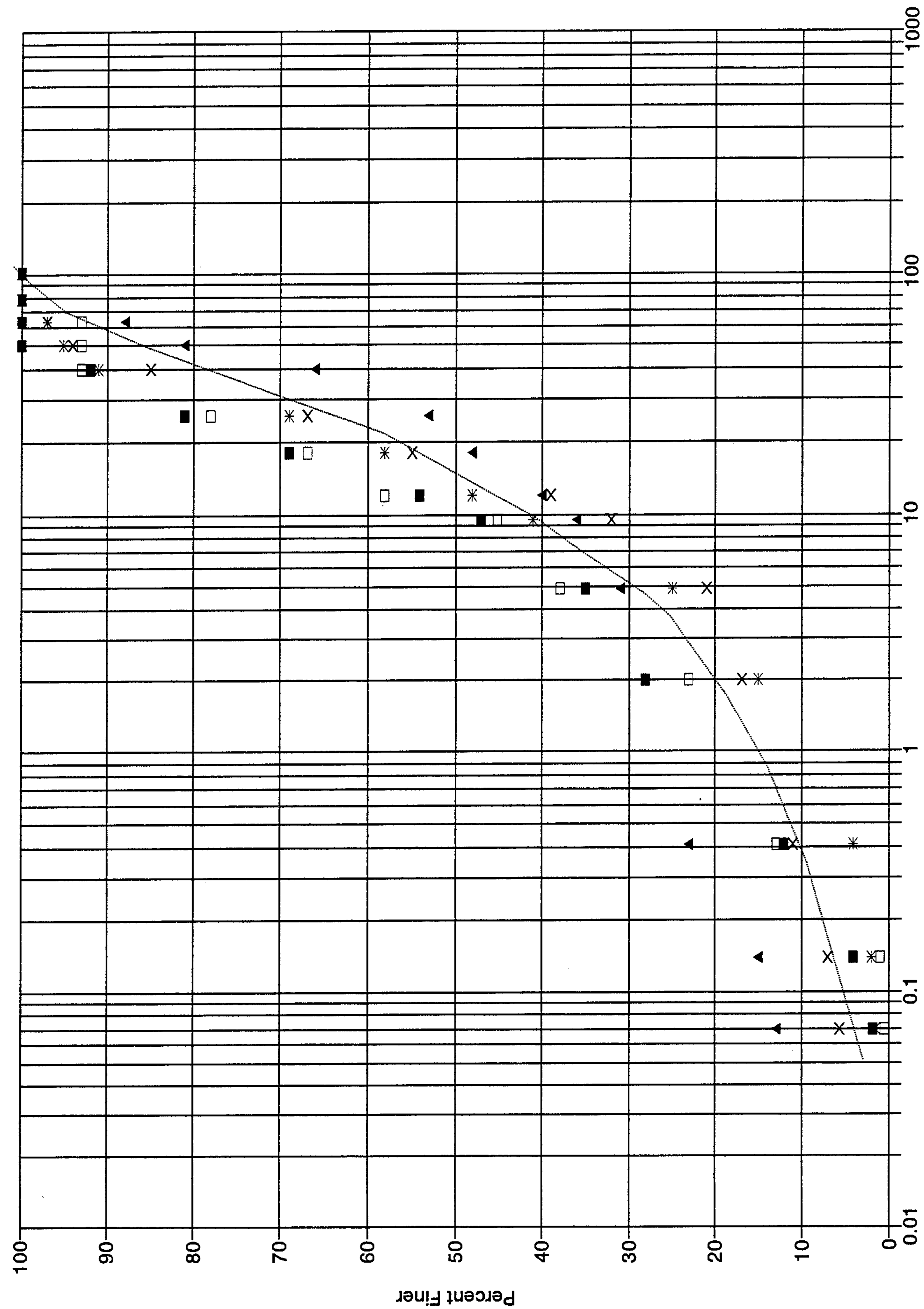


Figure 6.5
Representative Bed Material Gradation

Figure 6.5, this maximum wash load diameter is approximately equal to 0.2 mm. The soil survey data indicate, however, that the watershed soils are made up of 40% sands and gravels (D>0.062 mm), 20% silts (0.062 mm>D>0.004 mm), and 40% clay (D<0.004 mm). The wash load comes from active erosion sources within the watershed and is often associated with sheet, rill and interrill erosion processes. There is little information on how to account for the effects of the watershed sorting process upon the gradation curve of the wash load. With few exceptions, however, the watershed sorting process is accounted for by judgement or direct measurement and not by the modeling of distinct processes. The maximum particle size transported to streams by sheet flow can be estimated from samples taken from bar-like deposits in rills, roadside ditches, or low-gradient portions of the transport route.

This brings out an important point. There is an implicit assumption required here that since the wash load is controlled by the amount (or availability) of eroded sediments from the watershed, then land surface erosion methods can be used to estimate the potential wash load. This is a reasonable assumption to the extent that land surface erosion methods do not account for the natural sorting process that tends to trap larger grain sizes in the upper watershed and allow smaller particles to continue downstream. It follows, therefore, that the grain size distribution of soils in the upper watershed will generally be coarser than that of the wash load. Once again, use of measured data is recommended.

In this example, the following method is used to estimate the wash load gradation curve. The regional soil survey provided ranges of gradation for the dominant soil types as stated above. These ranges are plotted and used as a guideline for determining the slope of the gradation curve. Based on the Einstein criteria stated above, the D_{100} of the wash load can be estimated from Figure 6.5 as the D_{10} of the bed material, or 0.2 mm. Figure 6.6 shows the estimated wash load gradation resulting from this approximating procedure.

6.4.3 Gradation of Total Inflowing Load

Development of the grain size distribution for the total load estimate is perhaps the most difficult task in preparing the sediment input data for mobile boundary models. Direct procedures are lacking for estimating the grain size distribution for the inflowing load to a study reach. Use of field measurements is the most reliable procedure but may require large investments of time and money and is, therefore, impractical in many cases. The following discussions present two different methods for developing approximations of the distribution of sediment grain sizes for a given annual or single event yield. Method 1 presents a general approach suggested by Thomas and the Hydrologic Engineering Center (in Chapters 3 and 5 of CPD-6, 1993, and in Chapter 3 of TD-13, 1992). Method 2 has been used by others as an alternate procedure. Both procedures have inherent weaknesses and rely heavily on key assumptions that are difficult to verify. Whenever possible, engineers should try to verify their total load and grain size estimates with measured data.

Method 1: This method uses the HEC-6 program to develop its own inflowing load curve based on the assumption that the sediment supply reach for the model is in reasonable equilibrium. It uses that calculated inflowing load curve from HEC-6 to determine the annual yield of bed material load; and it subtracts that annual yield of the bed material from the total sediment yield (estimated separately; see discussions in Section 6.3) to determine the wash load. The weakness of this approach is that it lumps all fines into a

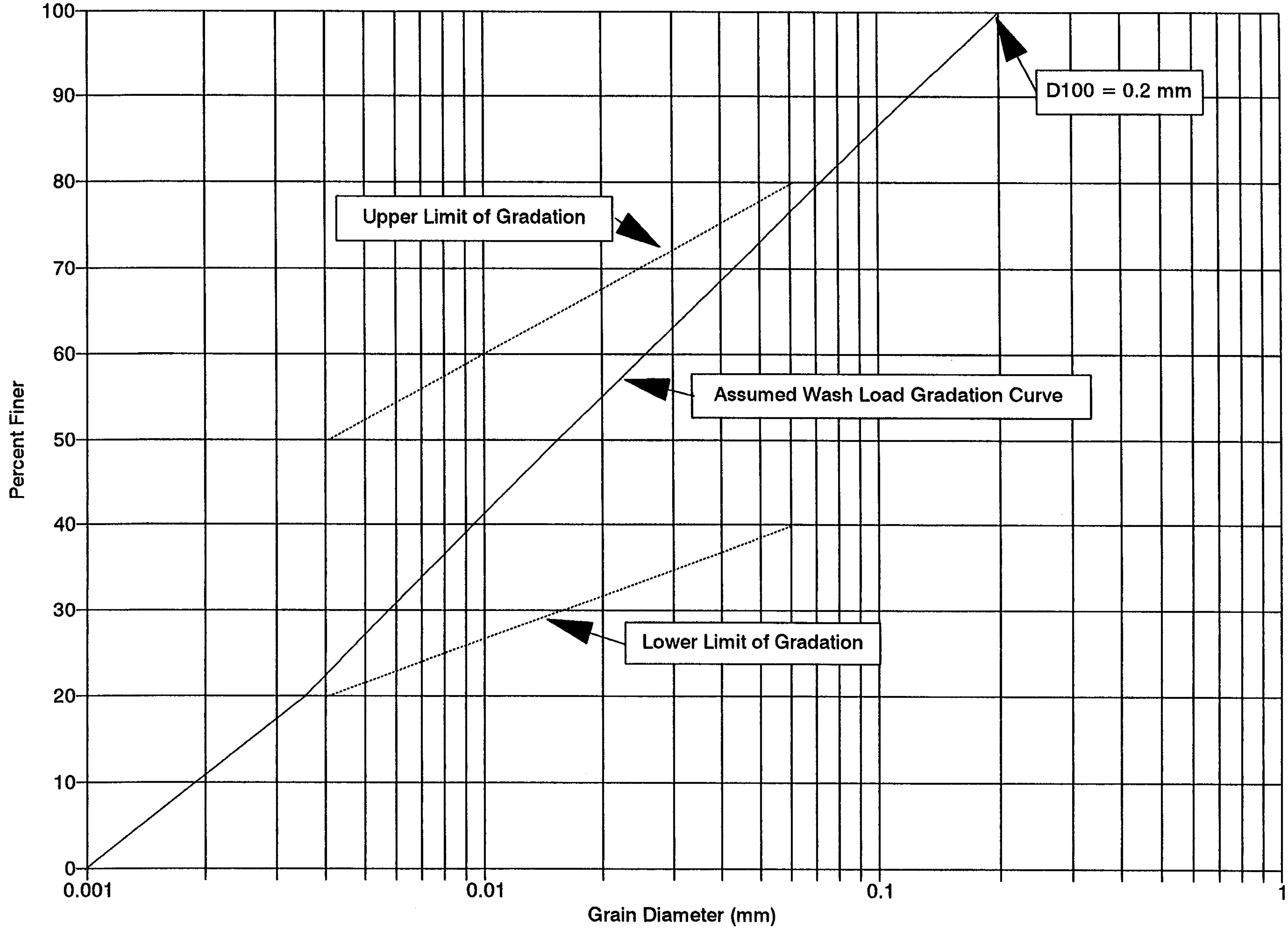


Figure 6.6
Wash Load Gradation Curve

wash load concentration which must then be distributed between clay and silt using the generalized soils data for the watershed, such as Figure 6.5.

This method requires that a reach of the river be identified in which the bed material discharge is in equilibrium and the bed material composition in that reach represents both the watershed and channel grain size characteristics. This reach (often referred to as the supply reach) is not required to be in the upper basin. It is, however, important to have an accurate water discharge in the selected reach which can be transposed to the inflow end of the model to maintain proper flow continuity. Annual peak flood frequencies are suggested for that purpose. These values usually decrease in the upstream direction as the drainage area decreases.

The supply reach should be at least as long as 20 river widths, or a hundred times the depth of the flow, whichever is longer. The requirement comes from flume experiments in which the flow-sediment mixture is allowed to stabilize over a distance equal to about 100 times the depth before water and sediment measurements are taken. Selection of the location and length of the supply reach is a judgement factor, not a theoretical law.

The bed gradation should be measured over this reach with a sufficient number of samples to develop representative gradation curves such as those shown in Figure 6.4. In sand bed streams, a dozen or so samples should be sufficient. In sand and gravel bed streams additional samples may be required because the data tend to scatter more. If the reach is in equilibrium, there should not be an upward or downward sloping trend in the D_{50} (mean grain diameter) data along it. If there is a trend, do not average curves from the samples taken along the channel. Keep them separate and develop averages from samples taken across the cross section. If there is no trend in D_{50} (e.g., D_{50} is fairly constant throughout the reach), average the bed gradation curves to develop one representative curve for the reach (such as shown in Figure 6.5).

It is important to link sediment transport computations with bed roughness when calculating bed material transport for sediment yield. HEC-6 does not permit such a linkage; therefore, use the SAM program (Thomas, et al, 1992) and develop the *n*-values for the reach for use in HEC-6. SAM also provides guidance for selecting the most appropriate sediment transport function from the velocity, depth, slope, width and D_{50} of the bed material in the reach being used as the equilibrium supply reach.

Next, run a series of steady flow calculations with HEC-6 using the annual flood peaks. Start with the 2-year peak and zero sediment inflow, and run a few days of time observing the sediment discharge passing each cross section in the interior of the model. Use the $VOL option to sum the total tons of sediment passing each cross section to calculate the rate of bed material transport by grain size. Change the inflowing sediment load from zero to that calculated rate and rerun the experiment. Make the same observations and calculations and modify the inflowing load curve again for the 2-year flood peak. A few iterations and the model should be transporting a uniform discharge past the selected cross sections with no significant change to the bed elevations at any location in the supply reach.

When satisfied with the model behavior at the 2-year peak discharge, repeat the procedure for higher and lower water discharges until the sediment inflow curve has been

developed over the full range of flows needed for the hydrograph analysis. Chapters 3 through 7 in HEC's TD-13 (HEC, 1992) present good examples of these procedures.

The SAM package contains a sediment yield program which takes a sediment discharge curve and integrates it with the annual flow duration curve, or a single event hydrograph, to calculate the sediment yield on an annual or single event basis, respectively. Naturally, if the sediment discharge curve represents only the bed material load, the sediment yield calculated will be the bed material yield. This value should fit within the total sediment yield calculated by the MUSLE or PSIAC or regression methods discussed in Section 6.3 or whatever methods have been used to estimate the total yield from the watershed.

There is no general rule that determines what percentage the calculated bed material load should be of the total load. Brown and Thomas (1981 and 1983) report that it can range from approximately 3% to more than 60% of the total load, depending on watershed conditions and the size and availability of material for transport. However, by inspecting available suspended load measurements in the region, one can judge whether or not the calculated value is reasonable.

It may be necessary to adjust either the calculated bed material load curve or the total annual sediment yield as determined by the other methods. For example, if the bed material yield is obviously too small a percentage of the total or too large a percentage, inspect the HEC-6 input data used to develop it. Adjust only to the extent that is reasonable. It may be necessary to change transport functions to bring the load into reasonable range. Once satisfied with the sediment discharge, convert the values to concentrations and transfer those concentrations to the inflowing end of the model using the water discharge which corresponds to the flow frequency of the calculations.

Method 2: The gradation of the total inflowing load can be determined by a weighted composite of the bed material and wash load gradation curves in Figures 6.5 and 6.6. In order to perform the weighted composite calculation the relative amount of bed material load as opposed to wash load must be estimated. There is no general rule that sets a specific percentage of the total load as bed material load. However, for many of the sand or sand and gravel streams with measured load data, the amount of bed material load often ranges from approximately 3 to 50 percent of the total load. Sediment load measurements from nearby or similar streams can often be used to verify the acceptable range for this ratio for a particular flow condition.

The sediment yield analysis in Section 6.3 concluded that from the MUSLE equation the total sediment load for the 100-year peak flow is approximately 6.8% by volume of the clear water flow. In general, this percentage will vary during the event with the highest concentrations of sediment occurring near the peak flow. Without measured data to support this, however, it is assumed that the percentage by volume of total sediment load is constant throughout the event. This is a reasonable assumption considering the concept that wash load is relatively independent of the hydraulic conditions in a channel.

If, for example, the measured water flow is 1,000 ft^3/s, the total sediment load is 6.8% of this, or 68 ft^3/s. Based on an assumed ratio between bed material load and total load for the example basin of 10%, this 68 ft^3/s is further divided into 6.8 ft^3/s of bed material load and 61.2 ft^3/s of wash load. Thus for any given flow, this weighting procedure can be used to

determine the rate of movement of both bed material load and wash load. Since gradation curves for each type of sediment load have been developed, these sediment transport rates can be broken into size classes. The amount of sediment in each size class for both wash load and bed material load are then combined in order to determine the gradation of the total load. Table 6.9 shows this breakdown. The column on the far right of the table is the total sediment load gradation. These data are then input into HEC-6 as a total inflowing load boundary condition. It is advisable to examine several assumed percentages for the assumed bed material load fraction and plot the resulting graduation curves to see if they are reasonable or match measured data from nearby or similar basins.

6.5 Sediment Transport Analysis

Prior to presentation of the example HEC-6 application, the following discussions are presented to remind readers of the procedures necessary to prepare and test a mobile boundary model such as HEC-6 for study applications.

6.5.1 Preparation of Model Data

Calibration and Performance Testing: Following the development of the basin sediment yield estimates and the necessary model input data, conduct model calibration and application procedures according to Chapters 4 and 5 in TD-13 (HEC, 1992). Check model geometry data for accuracy and completeness, then check the model's ability to duplicate natural river hydraulic conditions for low flow, bank full flow, and high flow. Begin testing using fixed bed computations first and then proceed to movable bed conditions. Apply SAM (WES, 1992) procedures to (a) select the most appropriate transport function, (b) estimate natural channel *n* values linked to channel roughness and bed form. Use methods outlined in Section 6.3.4 (Method 1 or 2) to develop the total inflowing sediment load curve and grain size distributions.

Once the total inflowing sediment load curve has been developed, it must be tested to see if the sediment load is compatible with hydraulic conditions of the channel (e.g., sediment transport capacity). If the mobile boundary model, (e.g., HEC-6) computes extreme amounts of scour or deposition at the upstream boundary then the inflowing load curve may not be in balance with the stream and adjustment is required. When this occurs, assume a different percentage for the bed material load, develop a new load curve for HEC-6, and test it again. Be sure the model is numerically stable before adjusting it.
Attend to hydraulic problems starting at the downstream end and proceeding toward the upstream end of the model. Reverse the direction for sediment problems. Do not worry about computed scour or deposition problems at the downstream end of the study reach until the model is demonstrating proper behavior upstream from that point.

Check the boundary conditions to determine that the particle size classes in the inflowing load are representative or approximate observed data. Correct any inconsistencies in the load or gradation data and try another execution. If computed transport rates are too high, check the field data for gravel content and determine whether an armor layer is developing. If deposition or scour rates are too high or low, check bank elevations and ineffective flow limits to ensure that the model is not allowing too much overbank flow to create excess channel deposits. Finally, if none of these actions produce acceptable

Table 6.9
Gradation of Total Inflowing Sediment Load by Size Class

Grain Size Classification	Minimum Grain Diameter (mm)	Maximum Grain Diameter (mm)	Fraction of Suspended Load in Size Class	Amount of Suspended Load for Peak Flow (cfs)	Fraction of Bed Load in Size Class	Amount of Bed Load for Peak Flow (cfs)	Fraction of Suspended Load in Size Class	Amount of Suspended Load for Peak Flow (cfs)
Clay		0.004	0.18	96.8			0.161	96.8
Very Fine Silt	0.004	0.008	0.12	64.6			0.108	64.6
Fine Silt	0.008	0.016	0.18	96.8			0.161	96.8
Medium Silt	0.016	0.031	0.14	75.3			0.126	75.3
Coarse Silt	0.031	0.062	0.14	75.3			0.126	75.3
Very Fine Sand	0.062	0.125	0.16	86.1	0.10	6.00	0.153	92.1
Fine Sand	0.125	0.250	0.08	43.0	0.02	1.20	0.074	44.2
Medium Sand	0.250	0.500			0.03	1.80	0.003	1.8
Coarse Sand	0.500	1			0.05	3.00	0.005	3.0
Very Coarse Sand	1	2			0.03	1.80	0.003	1.8
Very Fine Gravel	2	4			0.07	4.20	0.007	4.2
Fine Gravel	4	8			0.08	4.80	0.008	4.8
Medium Gravel	8	16			0.12	7.20	0.012	7.2
Coarse Gravel	16	32			0.25	15.00	0.025	15.0
Very Coarse Gravel	32	64			0.25	15.00	0.025	15.0
		Totals:	1.00	538.0	1.00	60.00	1.00	598.00

performance, adjust the ratio of inflowing bed material to total load and/or inflowing load curve. Attempt to match observed load data whenever possible.

Sensitivity Testing: During the course of the study it is advisable to perform a sensitivity test. Often, input data such as inflowing sediment load and gradation are not available. The estimating procedures outlined herein can be used to develop load and grain size distribution estimates, but it is important to assess the possible impacts of uncertainties in those values on model results. This simply requires modifying the suspected input data by +/- X% and re-running the simulation. If there is little change in the simulation results, the uncertainty in the estimated data is of no consequence. If large changes occur, however, the input data may require refinement and perhaps field verification (data collection).

6.5.2 Example HEC-6 Problem

An HEC-6 input file was prepared for the example problem described in Sections 6.1 and 6.2. The following data and information are used for this example:

- Geometry is taken from available HEC-2 applications (HEC, 1990b).
- Manning's *n* values are computed from SAM (WES, 1992).
- Inflowing sediment load volume and gradation are taken from Table 6.9.
- The Toffaleti and Meyer-Peter & Müller sediment transport function is used; see page 4 of HEC-6 user's manual (HEC, 1993).
- Bed material gradation is taken from Figure 6.5.
- The 100-year event hydrograph is used from previous HEC-1 applications (HEC, 1990a).

The HEC-6 input data file for this example problem is shown in Table 6.10.

HEC-6 Results: Computed bed elevation changes for the peak flow and at the end of the 100-year event are shown in Table 6.11. At the upstream boundary of the study reach, the results indicate 0.08 m (0.26 ft) of scour at the peak of the event, and 0.02 m (0.07 ft) of deposition at the end of the event. Based on the bed changes in adjacent cross sections it appears that the bed change near the upstream boundary are reasonable. This means the inflowing load is relatively well balanced with the streams' ability to transport it.

Develop a Base Test and Evaluate Project Alternatives: Had this example been a true project application, we would develop a base test to simulate the river under "no project - existing conditions." Following calibration and sensitivity testing analyze proposed project alternatives by comparing computed project performance results to base conditions.

6.6 Summary

This chapter presented an example of how to prepare the data and apply procedures to estimate inflowing sediment load and grain size distributions for use in mobile boundary models such as HEC-6. Readers should refer back to Chapters 4 and 5 for details on how to develop basin sediment yield and grain size estimates and how to evaluate sediment yield results, respectively. The example presented in Chapter 6 demonstrates those procedures

Table 6.10
Example HEC-6 Application Input File

```
T1B       EXAMPLE HEC-6 ANALYSIS
T2        DETERMINATION OF INFLOWING SEDIMENT LOAD
T3        AUGUST, 1994
NC  .015    .015    .015      .1      .3
X13454.0       4      .0    49.0       0       0       0
GR3913.5      .0 3899.52    14.0 3899.52    39.0 3909.46    49.0
H        3899.52
X13474.0       4      .0    57.0      20      20      20
GR3914.5      .0 3899.67    22.0 3899.67    47.0 3909.96    57.0
H        3899.67

 :
X1  31.9      11    2130    2650     290     390     380
X3    10
GR  4008    2000    4004    2075    4000    2130    3999    2175    3996    2340
GR  3996    2370  3992.8    2385  3992.8    2400    3996    2410    4000    2650
GR  4002    2920
H
X1  35.3      16    2030    2470     240     400     340
X3    10
GR4027.7    2000  4008.1    2030  4007.9    2060  4006.7    2100  4006.7    2120
GR4009.1    2170  4008.1    2200  4005.6    2210  4007.5    2250  4005.6    2290
GR4009.7    2320  4008.1    2360  4010.3    2400  4010.5    2470  4008.1    2500
GR4009.9    2530
H
EJ
T4       BED MATERIAL DATA FROM COMPOSITE OF FIVE SAMPLES
T5       TOTAL INFLOWING SEDIMENT LOAD BASED ON SEDIMENT YIELD ANALYSIS.
T6       HYDROLOGIC DATA IS BASED ON THE 100-YEAR FLOOD HYDROGRAPH.
T7
T8
I1          2000       0       0       0       0       2       1
I2             1       1       1    2.65       0               0      80       0
I3             1       1       4       0       0               0      90       0
I4            12       1      10       0       0       0       0     110
I5           0.5     0.5    0.33    0.33    0.33     0.5     0.5
LQ           359    3590
LT        116000 1160000
LF  CLAY    .198    .198
LFVFSILT    .144    .144
LF FSILT    .126    .126
LF MSILT    .108    .108
LF CSILT    .126    .126
LF   VFS    .115    .115
LF    FS    .092    .092
LF    MS    .004    .004
LF    CS    .003    .003
LF   VCS    .005    .005
LF   VFG    .005    .005
LF    FG    .013    .013
LF    MG    .012    .012
LF    CG    .022    .022
LF   VCG    .027    .027
PF        3454.0       1     600     100      90      40      77      20      60
PFC   10      43       2      24       1      19     0.2      10  0.0625       7
PFC .001      .1
$HYD
$B             2
*  AB        FIRST TIME STEP: 2,230 CFS FOR 45 MINUTES
Q   2230
R 3905.6
T     50
X .03125  .00625
*  AB        PEAK FLOW: 3,590 CFS FOR 25 MINUTES
Q   3590
R 3907.3
X .04861  .00347
*  AB        THIRD TIME STEP: 1,290 CFS FOR 45 MINUTES
Q   1290
R 3903.9
X .07986  .00625
*  AB        FOURTH TIME STEP: 400 CFS FOR 1 HOUR, 15 MINUTES
Q    400
R 3900.5
X .17361  .03472
$$END
```

Table 6.11
Example HEC-6 Application Output

```
****************************************************     **********************************
*  SCOUR AND DEPOSITION IN RIVERS AND RESERVOIRS  *      *  U.S. ARMY CORPS OF ENGINEERS    *
*       Version: 4.0.6  -  June 1991              *      *  HYDROLOGIC ENGINEERING CENTER   *
*  INPUT FILE:  FP39-H6.DAT                       *      *  609 SECOND STREET               *
*  OUTPUT FILE: FP39-H6.OUT                       *      *  DAVIS, CALIFORNIA 95616-4687    *
*  RUN DATE: 18AUG94       RUN TIME: 12:58:09     *      *  (916) 756-1104                  *
****************************************************     **********************************

                      X     X  XXXXXXX   XXXXX          XXXXX
                      X     X  X        X     X        X     X
                      X     X  X        X              X
                      XXXXXXX  XXXX     X       XXXXX  XXXXXX
                      X     X  X        X              X     X
                      X     X  X        X     X        X     X
                      X     X  XXXXXXX   XXXXX          XXXXX


T1B        EXAMPLE HEC-6 ANALYSIS
T2         DETERMINATION OF INFLOWING SEDIMENT LOAD
T3         AUGUST, 1994
```

⋮

```
==========================================================================================

*   AB       PEAK FLOW: 3,590 CFS FOR 25 MINUTES

COMPUTING FROM TIME=      .031250 DAYS TO TIME=      .048610 DAYS IN         5 COMPUTATION STEPS

  SECTION   BED CHANGE   WS ELEV   THALWEG        Q          SEDIMENT LOAD (TONS/DAY)
   ID NO       FEET       FEET     EL FEET       CFS          CLAY       SILT       SAND
    35.300       -.26    4009.10   4005.34      3590.     229680.    584640.    329535.
    31.900       -.38    3997.88   3992.42      3590.     229680.    584640.    391570.
    28.100       -.24    3980.86   3977.46      3590.     229680.    584640.    520723.
    22.100       -.15    3959.65   3955.45      3590.     229680.    584640.    598894.
    18.300        .66    3945.85   3942.66      3590.     229680.    584640.    500758.
    16.800      -3.86    3939.20   3932.04      3590.     229680.    584640.    665136.
  4677.000      -2.04    3935.90   3931.46      3590.     229680.    584640.    511102.
  4550.000       -.37    3935.52   3925.13      3590.     229680.    584640.    444895.
  4400.000        .08    3935.36   3914.04      3590.     229680.    584640.    272939.


==========================================================================================

*   AB       FOURTH TIME STEP: 400 CFS FOR 1 HOUR, 15 MINUTES

COMPUTING FROM TIME=      .079850 DAYS TO TIME=      .173610 DAYS IN         2 COMPUTATION STEPS

  SECTION   BED CHANGE   WS ELEV   THALWEG        Q          SEDIMENT LOAD (TONS/DAY)
   ID NO       FEET       FEET     EL FEET       CFS          CLAY       SILT       SAND
    35.300        .07    4007.22   4005.67       400.       25591.     65141.     35765.
    31.900       -.65    3994.50   3992.15       400.       25591.     65141.     41700.
    28.100       -.36    3979.84   3977.34       400.       25591.     65141.     48946.
    22.100       -.21    3957.23   3955.39       400.       25591.     65141.     49410.
    18.300       1.58    3944.74   3943.58       400.       25591.     65141.     38044.
    16.800      -5.90    3934.83   3930.00       400.       25591.     65141.     46751.
  4677.000      -1.64    3933.63   3931.86       400.       25591.     65141.     40219.
  4550.000       -.37    3928.36   3925.13       400.       25591.     65141.     38271.
  4400.000       4.92    3928.36   3918.88       400.       25591.     65141.     20097.

$$END

       0    DATA ERRORS DETECTED.

WARNING: SILT+CLAY CONCENTRATIONS IN EXCESS OF     50000. PPM WERE DETECTED     340 TIMES.
         MUDFLOW CONCENTRATIONS (SILT+CLAY IN EXCESS OF  800000. PPM) WERE DETECTED       0 TIMES.

TOTAL NO. OF TIME STEPS READ =          4
TOTAL NO. OF WS PROFILES =             17
ITERATIONS IN EXNER EQ =          680000.
END OF JOB

JOB COMPLETED
RUN TIME =  0 HOURS,  1 MINUTES & 45.68 SECONDS
```

outlined in Chapter 4. CPD-6 (HEC, 1993) and TD-13 (HEC, 1992) present details required for preparing data and calibrating and applying computer program HEC-6. HEC-6 is designed to simulate and predict changes in river profiles resulting from scour and/or deposition over moderate time periods (typically years). Single event analyses are possible, however, calibration data are rarely available for single event analyses. Readers are encouraged to rely on measured field data whenever and wherever possible when preparing input for mobile boundary model applications.

Chapter 7

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Appendix A

"A Review of Watershed Erosion Models"
by
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A REVIEW OF WATERSHED EROSION MODELS[1]

I. INTRODUCTION

This paper presents the results of the first stage of the Hydrologic Engineering Center's Land Surface Erosion R&D work unit No. 32773.

Increased awareness of environmental impacts of land surface erosion has prompted the development of comprehensive computational models to evaluate the effects of sediment discharge in watersheds. Mathematical models or formulae which are used to estimate sediment discharge rates from a watershed, and the redistribution of soil within a watershed are being increasingly utilized by land and water resource managers to evaluate the consequences of their management decisions. The objective of this work unit is to develop analytical procedures that can be incorporated into computer routines which estimate sediment discharge from a watershed on an annual basis and/or for specific single events. The initial phase of this work unit involves the review of current numerical models, and past research and applications in the study of land surface erosion. This review will then be employed as a decision making tool to evaluate the best course of action to take to complete the objective of the work unit.

This paper is a reflection of the literature search performed. A review of present literature is initially undertaken. This is followed by a precursory review of related watershed erosion models and a more in-depth review of selected current watershed erosion models.

II. LITERATURE REVIEW

On watershed hillslopes, the sedimentation process begins on overland flow areas with detachment of soil particles through raindrop impact or flow shear, and subsequent entrainment by overland flow. As overland flow concentrates in small channels (or rills), transport and deposition occur. Entrainment and transport of sediment particles is a function of particle size, soil cohesion, slope

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parameters, and forces exerted on the particle by flow. When the forces of the flow are diminished below a threshold value, i.e., when sediment load exceeds sediment transport capacity, the settling process predominates and net deposition occurs. Any attempt to model sedimentation processes as they naturally occur in watersheds is seriously constrained by variables and processes that may change rapidly with time and vary spatially at a wide range of scales. Therefore, simplified representations are commonly used to model the complex processes of sediment generation, transport, and deposition.

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) is a simple mathematical expression which is the most widely used method for estimating total annual sediment discharge. The Modified Universal Soil Loss Equation (MUSLE) (Williams 1975) is an altered form of the USLE for applications to single storm events. The USLE is an empirically based lumped model which does not define separate hydrological processes such as rainfall, infiltration, and runoff, or fundamental erosional processes such as detachment by raindrop impact, detachment by flow, and sediment transport and depositional processes.

Research in the field of land surface erosion has progressed to focus on the physical processes which influence sediment detachment and transport. Yalin (1963) formed a widely used equation which represents the transport capacity in an erosive model through combining rill and interrill flow. Continuing research on interrill erosive processes such as raindrop impact and sediment delivery by Palmer (1965), Young and Wiersma (1973), Mutchler and Young (1975), and Walker et al. (1977) among others indicated that conditions of interrill transport differ from fluvial transport in two areas: soil surfaces in interrill areas are generally more cohesive and finer grained than alluvial bed material, and transporting forces are supplied both by flow and raindrop impact in the interrill areas.

Moore and Burch (1986) developed a simple, physically-based, analytical procedure which included the effects of topography on erosion and deposition over a landscape. Yang's sediment transport equation (1973), which is based on unit stream power theory, was adopted as the theoretical basis from which analytical functions were derived for characterizing topographical influences. Soil detachment and ground cover effects were ignored in order to simplify the analytical procedure. The results of the application of these functions to hypothetical and real landscapes indicated that hillslope shape, slope length, and catchment convergence and divergence play important roles in determining total soil loss from a hillslope or catchment and the relocation of soil within the catchment.

Alonso, Neibling, and Foster (1980) evaluated the predictive capability of nine sediment transport formulas through comparison with flume and field data. The comparison was based on 40 field measurements, 523 flume experiments, and 176 tests on concave slopes, with sediment ranging from coarse sands to very fine soil particles. Formulas evaluated were the total load formulas of Ackers and White (1973), Engelund and Hansen (1967), Yang (1973), Laursen (1958), Einstein (1950), and the bed load formulas of Meyer-Peter and Müller (1948), Bagnold (1956), and Yalin (1963). Because of the dependence of sediment transport rates on many hydraulic and sediment related variables, the forms of the

existing formulas depend upon the relative importance assigned by the authors which makes it impossible for a single formula to be applicable to the large range of possible conditions that may be encountered. Results have indicated that the Yalin formula performs satisfactorily in computing sediment transport capacity for overland flows for the range of characteristic field conditions. The Yang (1973) formula best estimated streamflow carrying capacity in the range of fine to coarse sands. The Laursen formula reasonably predicted situations involving small streams carrying very fine sands and silts.

Guy, Dickerson, and Rudra (1987) performed a study to measure the transport capacity of interrill flow generated under simulated rainfall, and to isolate the contributions to transport capacity from raindrop impact and surface runoff. Their finding indicated that 85% of the erosion that occurs in interrill areas is attributable to raindrop impact, and the degree of enhancement of transport capacity in interrill areas by raindrop impact was dependent upon rainfall intensity and bed slope.

Kinnell (1991) developed an analytical model supported by laboratory data on erosion by rain-impacted flows incapable of entraining soil material. Results indicated that the transport of sand increased linearly with both rainfall intensity and flow velocity. The data also showed that, for medium-to-large sized raindrops travelling at close to their terminal velocities, flow depth also has a significant effect on the transport of particles when the flow depths are smaller than the drop sizes.

Govindaraju, Kavvas, Tayfur, and Krone (1991) performed a hillslope experiment and analysis which emphasized the key role of rill formation in sediment transport. The field test was conducted on a freshly cut slope of decomposed granite. Varying quantities of water were manually sprayed over the slope exposing the slope to rainfall simulations ranging in intensity from 1 to 6 in/hr for 12 minute intervals. Measurements conducted during each simulation were: average rain intensity, sediment discharge at the downstream end, and soil moisture contents at 9 stations spatially dispersed across the slope. Immediately following each rain event, the spatial density and geometry of the rill patterns were measured along the slope. This data was then analyzed for statistical significance. The concept of Expected Spatial Rill Density (ESRD) was introduced for straight homogeneous hill slopes. ESRD is an averaging process which represents the rill occurrence probability over a particular transect as a function of the hillslope averaging interval. The experiment found that rill geometries have little variance over large portions of the hillslope. The mean depth of the rills increased with increasing hillslope length. However, this increase is very rapid at small slope lengths from the top of the hillslope, and as the distance from the hillslope increases, the mean values for the rill widths and depths almost reach equilibrium. An ergodic scale was introduced that allowed the potential replacement of varying microtopographic parameters with representative averages. Statistical analysis of experimental results indicated the existence of an ergodic length scale for the hillslope in terms of the ESRD. Further results from the statistical analysis of experimental values indicated a roughly linear relationship between: sediment losses and rainfall intensity, slope length and sediment discharge, and surface roughness and sediment discharge. A methodology for predicting overall water and sediment loss from a hillslope was developed. The paramount conclusion from the experiment was that flow and sediment transport parameters are prominent

in rills in relation to overland flow sections. Thus, the authors concluded, the use of conventional sheet flow models at the hillslope scale has the potential for large error in sediment discharge estimations.

The rapid advancements in computer technology over the past 20 years has allowed for the widespread application of state-of-the-art erosion prediction technology. There are many hydrologic models available today that have the capability of simulating sediment discharge, transport, and deposition in a watershed. Combined sheet and rill erosion can be predicted through the use of empirically-based models or physically-based models. An indicator of physically-based models is the subdivision of the surface into rill and interrill areas of separate erosion processes. The following is a short, chronologically arranged, review of watershed erosion models found in the literature search. An in-depth review of six current models, which have the capability to model single storm events, is presented in the next section.

A finite element numerical model to simulate erosion processes in a watershed was developed by Ross, Shanholtz, and Contractor (1980) through the incorporation of FESHM- a Finite Element Storm Hydrograph Model (Li 1975). This model is spatially responsive and has a flexible grid structure which allows the representation of major spatial variations and enables the modeling of sediment discharge in both upland and lowland areas. Sediment detachment is represented in FESHM as a function of raindrop impact and overland flow. Sediment discharge is then routed through a channel by using a continuity equation.

ANSWERS - An Areal Nonpoint Source Watershed Environmental Response System (Beasley, Huggins, and Monke 1980) is a deterministic, distributed parameter model which was designed for short-term, single event simulations on small watersheds. ANSWERS divides the watershed into rectangular grid elements with uniform characteristics in an effort to model the spatially varying processes of runoff, infiltration, subsurface drainage, and erosion. A finite difference approximation scheme is utilized for evaluating continuity of flow within and between elements. The overall structure consists of a hydrologic model, a sediment detachment/transport model, and routing components. The hydrologic model incorporates variables which influence surface flow including interception, infiltration, and surface retention and detention. Sediment detachment can be accomplished by either raindrop impact or overland flow. The splash erosion rate is dependent on rainfall intensity, slope gradient, raindrop size, and water depth on bare soil. Detachment of soil particles by overland flow occurs when the shear stress at the surface overcomes the gravitational and cohesive forces on the particles. Channel erosion is also included. If sediment load becomes greater than transport capacity, deposition occurs. Total sediment discharge is routed through the watershed by use of a continuity relationship.

In recent years, significant progress has been made in the understanding and description of individual rill growth and development. A computer model to simulate upland erosion was developed by Khanbilvardi, Rogowski, and Miller (1983). The hydrologic portion of the model computes infiltration and determines runoff as a function of rainfall excess i.e., the difference between rainfall rate and infiltration. The model is based on dividing the upland area into a grid containing rill and interrill zones.

The model uses a procedure to identify rill sources and likely paths that they would follow. The formation and location of a rill is a function of slope steepness, soil erodibility, and the amount of energy in the overland flow. Rill flow velocity and depth is computed through the use of Manning's equation. Rill transport capacity is based on the Yalin equation (1963) and is a function of hydraulic radius, slope, and particle diameter. Rill detachment occurs when the shear stress due to flow exceeds the critical shear stress for sediment transport. Interrill erosion is said to occur due to the detachment of soil by raindrop impact and the transport of these sediment particles into the rills. The model specifies zones adjacent to rills from which sediment and runoff can be contributed and calculates the amount of sediment discharge from these small areas through the Universal Soil Loss Equation (USLE). Routing to the downslope area was performed through the use of a continuity equation. Khanbilvardi and Rogowski (1986) developed a similar model which divided the watershed into a series of square subareas, the sizes of which vary depending upon terrain and amount of detail available. A node was located at the center of each square and represented the parameters and sediment discharge as constants over each square. The model assumed that the rill pathways delineated the only flow systems at the site. Soil available for transport at the rill nodes is calculated using the USLE and routed to the watershed outlet. Predicted values of sediment yield for individual storms over a 10-year period agreed well with the experimental data for two agricultural watersheds.

An upland soil erosion simulation model for agricultural watersheds was interfaced with the USDAHL-74 watershed hydrology model by Yoo and Molnau (1987). The erosion model used the rainfall intensity and the overland flow rate obtained from the hydrology model to estimate sediment detachment and transport. The model considers temporal and spatial variations in canopy cover, moisture content, and snow cover and evaluates their effects on raindrop impact and overland flow erosive forces. In the hydrology model, the watershed can be divided into a maximum of four hydrologic zones, and each zone is provided with a set of hydrologic and field parameters. The hydrology model was modified to include estimations of snowfall, snowmelt, soil moisture content, subsurface flow and daily temperature distribution. The overland flow simulated by the hydrology model for each hydrologic zone was separated into rill and interrill zones based on the temporal changes of the ratio of rill area to total area, and average rill depth. In interrill areas, soil particles could be detached by raindrop impact, or overland flow. Yalin's equation (1963) was used to determine the transport capacity of rill flow. The availability of soil particles in detachment storage, rill flow transport capacity and sediment load were compared to determine the fate of the detached particles. Erosion due to channel flow was also considered in the model through the use of the critical flow concept. The model assumes that no channel deposition occurs. Therefore, total sediment discharge at the watershed outlet is the sum of channel erosion and sediment transported to the channel by rill flow to the channel.

WINHUSLE, the Wisconsin Nonpoint sediment yield model (Baun 1991), estimates instream sediment yield throughout rural watersheds and sediment delivery from individual fields to designated downstream points. WINHUSLE runs on either a single event or average annual basis, under either existing or alternative land management practices. Notable attributes of the model are its use of input data

based on hydrologic areas rather than grid cells, and its use of geomorphic relationships to describe hydrologic parameter values. Polygonal based input data allows for more homogeneous data collection, and for the size and shape of the hydrologic area to correspond to the diversity of the landscape. Input data to each delineated hydrologic area consists of USLE parameters, total drainage area and channel characteristics. WINHUSLE has the added ability of using hydrogeomorphic relationships which approximate unknown hydrologic parameters such as channel length, slope, hydraulic radius and Mannings *n*. The sediment yield predicted by the model employs an accounting system based on conservation of mass for hydrologic areas in parallel and series. For hydrologic areas in series, deposition losses from upper areas as they flow across the lower areas are taken into account through the computation of a composite sediment yield value for the series system.

Wright and Krone (1989) constructed a simple empirical model of erosion processes in upland areas. A surface runoff sub-model based on overland flow theory, and a sediment transport sub-model based the conservation of mass and sediment continuity are employed. The quantity of sediment due to soil splash is included as a parameter in the sediment transport sub-model and is based upon an empirical equation proposed by Bubenzer and Jones (1971).

SWRRB-Simulator for Water Resources in Rural Basins (Arnold, Williams, Nicks, and Sammons 1990) was designed by the Agricultural Research Service (ARS) as a tool to predict the effect of management decisions on water and sediment yields for ungaged rural basins. It is primarily a long-term water and sediment yield simulator. Precipitation and temperature values can be generated from long-term weather data, or daily precipitation parameters may be specified by the user. Output of runoff and sediment discharge can range from daily to yearly time scales. SWRRB is a comprehensive model which covers all aspects of the hydrologic cycle. This includes surface runoff, percolation, return flow, snowmelt, evapotranspiration, transmission losses, pond and reservoir storages, and crop growth. SWRRB is not limited by drainage area. The model contains the provision for subdividing basins where each subbasin can use separate rainfall data. Surface runoff for each subbasin is predicted for daily rainfall using the Soil Conservation Service (SCS) curve number formula. Peak runoff rates are based on the Rational formula. Sediment yield is computed for each subbasin through the application of the Modified Universal Soil Loss Equation (MUSLE). Sediment size is distributed among five grain sizes for computational and tracking purposes. SWRRB also has the capability to route sediment through reservoirs.

Hrissanthou (1988) developed a simple empirically based model which was applied to a Middle European watershed. Due to the nature of the watershed data, stream and gully channel erosion were neglected. Processes simulated by the model include: surface runoff from rainfall through application of the model of Lutz (1984), combined sheet and rill erosion at the outlet from the Modified Universal Soil Loss Equation (MUSLE), and sediment routing and deposition through the application of the sediment routing model of Williams (1975).

Lopes and Lane (1988) developed a physically-based, event oriented mathematical model for small watersheds. Partial differential equations describing the unsteady and spatially varying sedimentation processes are employed rather than the conventional approach using steady state transport functions. Numerical solution of the partial differential routing equations is performed through the finite difference method. The model assumes that sediment flux can be represented approximately without explicit description of rill features. Sediment entrainment by overland flow is accomplished by detachment by raindrop impact or by the shear stress of the flow.

PRORIL, a probabilistic physically based erosion model was developed as a masters' thesis by Lewis (1990) at the University of Kentucky. In this model, two random characteristics, rill density and rill flow, are used to stochasticaly represent the rill network. The development of probability density functions to represent in-field rill density and rill flow rates was addressed by Lewis, Barfield, and Storm (1990). A rainfall simulator erosion study was conducted by the University of Kentucky from May 1987 through October 1988 (Storm, Barfield, and Ormsbee 1990). Data collected from twelve bare soil runs included runoff rates, effluent sediment concentration and visual interpretations of rill network development. This data was then applied to a digital elevation model to obtain probabilistic outputs of rill density and rill flow rates. The digital elevation model, using geographic information system software previously limited to use on large scale areas, was found to be applicable to use of field scale topographic data to estimate concentrated flow paths and flow rates on a microscale. This type of application allows for data generation of rill density and rill flow rates for use in erosion studies and models.

DYRT, a Dynamic Erosion Model, is a physically based model developed by Storm (1991) at the University of Kentucky. DYRT provides the capability to predict erosion rates and sediment yield for varying surface conditions and has the ultimate purpose of evaluating new and existing tillage systems without extensive field measurements. In addition, the model can be applied to the assessment of the impacts of rill density, surface roughness, rill network development, and numerous other erosion sub-processes on sediment yield. DYRT contains a deterministic erosion component which is applied to a stochasticaly generated random surface. The random surface is generated using a defined random roughness and correlation length for a specified covariance function. The resulting flow networks are defined with a digital elevation model applied to the generated surface (Storm 1991). Interrill erosion is simulated by using a modified form of the Meyer (1981) equation which circumvents describing the complex individual physical processes and provides a net interrill sediment delivery to the concentrated flow network. The Foster and Lane erosion model (Foster 1982) is used to model rill erosive processes. The rate of potential rill detachment is based on shear excess. An equation for shear distribution was employed (Foster and Lane 1983) to estimate shear excess along the rill boundary. Rill characteristics were formulated through the use of a conveyance function for specified flow and soil parameters. Rill development continues primarily vertically until the rill reaches a nonerosive layer, where lateral rill expansion becomes dominant. The Yalin (1963) equation was selected to quantify the transport capacity of rill flow. Sediment routing is accomplished through the use of the steady state continuity equation for mass transport, which was revised to address the interaction between sediment and transport capacity.

III. REVIEW OF SELECTED WATERSHED EROSION MODELS

As stated previously, the objective of this work unit is to develop analytical procedures, that can be incorporated into a computer routine, which simulate sediment discharge from a watershed due to a single storm event. The following six current watershed models were selected as a representation of the range of models available which have the ability to meet work unit criteria.

The Simplified Process Model

A Simplified Process (SP) Model for Water Sediment Yield from Single Storms was designed in 1987 by David M. Hartley of the USDA. It is a simple empirical model which predicts upland sheet and rill erosion for single storms. Soil detachment by raindrops and surface runoff is taken into account. Channel transport is not taken into account. Data input requires 20 parameters, as compared with 6 parameters for the Universal Soil Loss Equation (USLE). Data input is organized under 6 categories: rainfall data, infiltration parameters, topography and surface parameters, vegetation parameters, sediment parameters and fluid properties.

The SP model utilizes an idealized trapezoidal shaped storm hydrograph. Runoff begins after a series of delays caused by interception, soil ponding and depression storage. Maximum runoff is computed as a function of runoff depth and total runoff time. Both the sediment transport capacity and sediment supply due to rainfall and runoff erodibility is calculated with the smaller of the two used to represent the sediment yield for the storm event. Sediment transport capacity is calculated as a function of the shear and critical stresses of the soil. The sediment supply is determined as a summation of rainfall and runoff detachment rates. The rainfall detachment rate is calculated as a direct function of the rainfall energy rate (as adopted from the USLE), ground cover, a canopy factor, and a soil erodibility factor. The runoff detachment rate is determined as a function of slope, the USLE K factor, runoff flow, and a soil erodibility factor.

A comparison of the Simplified Process Model with the USLE illustrated some important differences between the two. The SP soil loss estimates are sensitive to antecedent soil moisture while the USLE is not. Thus, the soil loss estimates for wet soil conditions are much greater in the SP model. Secondly, the SP does not use a strictly linear relationship, as does the USLE, in estimating the increased magnitude of soil loss in extreme topographic conditions. Factors such as whether the sediment transport capacity limits soil loss, and the relative contributions of raindrop versus runoff detachment, are also considered along with slope parameters.

The Simplified Process Model is a direct, user-friendly, empirical model which was designed to account for the most important physical processes contributing to erosion in a single storm event, as

opposed to the USLE which was designed to estimate average annual erosion. The model exhibits physically appropriate sensitivity of both runoff and sediment yield to antecedent soil moisture conditions. Its strength lies in its potential to calculate sediment yield from a watershed with little computational effort.

AGNPS-An Agricultural Non-Point Source Pollution Model

AGNPS (Young, Onstad, Bosch, and Anderson 1987) is an empirically based, single event watershed runoff, erosion, and pollution transport model developed and continuously updated by the USDA Agricultural Research Service (ARS). The ARS is currently working on a new generation of AGNPS that will simulate erosion, transport, and the depositional process on a continual basis. AGNPS was developed primarily as a comparative analysis tool and not a predictive model.

AGNPS employs a framework of square uniform cells to represent the watershed area. Flow direction in each cell, in relation to neighboring cells, is specified. Runoff and sediment transport characteristics are simulated for each cell and routed to the outlet through use of continuity equations. This permits the examination of flow and sediment transport at any cell within the watershed. Calculations made by AGNPS occur in three loops. In the first loop, initial estimates for all cells and overall runoff volume are made. The second loop computes sediment yields for upland primary cells (a cell that no other cell drains into), and runoff volume from cells containing impoundments. In the third loop, sediments and nutrients are routed through the watershed and calculations are made to derive the channel transport capacity and actual flow rates.

Two types of input are required for AGNPS, watershed data and cell data. Watershed data consists of precipitation input which is distributed uniformly over the watershed. Input for each cell includes: the SCS curve number, topographic data, Manning's coefficient, channel and bank slope, the soil erodibility factor, and soil texture. Hydrological output provides estimates of runoff volume and peak runoff rates. Erosion output includes estimates of upland erosion, channel erosion, and sediment yield. Results are available for a single cell or the entire watershed. Runoff volume estimates are based on the SCS curve number method (USDA 1972), and are routed through the watershed through use of a continuity relationship. Peak runoff for each cell is also estimated empirically.

AGNPS calculates total upland erosion and total channel erosion for 5 separate particle size groupings. Upland erosion is estimated for each cell by the Modified Universal Soil Loss Equation (MUSLE). Soil loss is calculated for each cell and routed downgradient. In channels, effective transport capacity is computed using the Bagnold stream power equation. Deposition rate is estimated as a function of flow, particle fall velocity, and transport capacity. Total sediment load is then routed to the outlet through use of the steady-state continuity equation.

RUNOFF- A Single Event Runoff and Sediment Transport Model for Small Watersheds

The model RUNOFF is a largely empirical, single event, model with the capability to estimate runoff and sediment discharge from the headwaters of the watershed to the outlet. RUNOFF was developed by D.K. Borah and M.S. Ashraf of Rutgers University in 1990. A RUNOFF3 version of the model is currently in the final stages of development. The model works on a segmented basis where the watershed is divided into a series of representative elements of overland flow and channel flow segments to account for spatial topographic, soil and land use non-uniformities. These elements are treated as being homogeneous in topographic, soil, and land use characteristics. The model is also capable of routing runoff, but not sediment, through reservoirs.

The watershed runoff portion of the program uses either the SCS curve number procedure or the subtraction of interception and infiltration values to estimate upland runoff. Overland and channel flow is routed by use of the physically-based kinematic wave approximations of the St. Venant equations. Solution is performed analytically through the method of characteristics. A shock-fitting scheme is used to route shocks that develop during the course of the computation.

Sediment transport is estimated concurrently with the runoff simulation in each flow element. In the overlands, sediment is discharged through raindrop impact and shear stress generated by flowing runoff. Detachment by raindrop impact is computed as being proportional to the square of the rainfall intensity. Erosion due to raindrop impact continues until rainfall ceases or water depth on the ground is deep enough to absorb the kinetic energy of the raindrop. Erosion will decrease until it reaches zero when the water depth is three times the average radius of the raindrops. Erosion due to shear stress is a function of the transport capacity of the flow and soil erosion due to flow detachment. If flow capacity is greater than sediment discharge, erosion takes place. If sediment discharge is greater than the transport capacity, deposition takes place. Sediment transport capacity values in overlands is computed using the bed load formula of Yalin (1963). Loose soil accumulated by the detachment of bed materials by raindrop impact and previously deposited sediment is accounted for in the model as a detached soil depth. These loose soils are routed downstream by a flow of sufficient transport capacity. A flow detachment coefficient is used to compute the much higher energy required to produce erosion from the undetached materials of the original bed. In channels, transport capacity for sediment sizes equal to or larger than 0.1 mm is computed using the total load formula of Yang (1973). Smaller sediments use the total load formula of Laursen (1958).

Up to five groups of sediment sizes can be represented in the model. Each group is represented by its median size and is computed independently from the remaining sediment fraction. Sediments are routed along with the water runoff based on an analytical solution of the continuity equation for each fraction of sediment size. Total sediment discharge is computed by adding the discharges of each sediment group.

WEPP- The Water Erosion Prediction Project

The Water Erosion Prediction Project (WEPP) is a current program implemented by the USDA with the objective of developing an improved erosion prediction technology based on modern hydrologic and erosion science which is conceptually a significant improvement over the USLE. Since the model is intended to be used by the Soil Conservation Service (SCS) as a replacement of the USLE, model execution time is a major factor in model development. Thus, although the model is physically-based in that the governing equations are the conservation of mass and energy, empirical relationships and approximations are used to reflect those erosional processes which are too complex or varied to be represented by a simple differential equation.

The most recent literature about WEPP indicates that there are three major components of the program: a hillslope component, a channel component, and an impoundment component. The hillslope component is the only component which has been distributed, and will be discussed in detail in the remainder of this review. The WEPP hillslope profile model was designed with the intention of being a continuous simulation model, although it can be run on a single storm basis. The model was designed to be applied to fields of up to 2,000 acres in size. However, a recent extension to the hillslope profile model, called the WEPP watershed model, does not have these size constraints and is intended for use on small (<2.00 acres) agricultural watersheds in which sediment yield at the outlet is significantly influenced by hillslope processes. WEPP consists of six sub-programs: climate generation, hydrology, plant growth, soils, irrigation, and erosion. WEPP has the capability for estimating spatial and temporal distribution of soil loss. The model does this by dividing the hillslope or watershed into overland homogeneous flow elements which are rectangular strips. Each element is treated as an independent hillslope, and up to 10 elements are allotted for each simulation. Flow and transport in perennial streams or channels is not accounted for in this model.

The hydrology component of WEPP calculates infiltration, evapotranspiration, deep percolation, daily water balance and runoff. Infiltration is calculated by the Green and Ampt equation. Runoff is calculated using the kinematic wave equations, or by approximating the analytical solution for a range of rainfall intensity distributions, hydraulic roughness, and infiltration values. WEPP does not allow for perennial streams in the watershed model.

Three hydrologic variables are required for sediment discharge computations: peak runoff rate, runoff duration, and rainfall intensity. The governing equations used to estimate erosion parameters are: sediment continuity, detachment, deposition, shear stress in rills, and transport capacity. The sediment continuity equation represents the sediment load at a point on a slope as a function of erosion rate and interrill erosion rate. Soil detachment in rills is calculated for the case when hydraulic shear exceeds the critical shear stress of the soil. Net deposition occurs when the sediment load exceeds the sediment

transport capacity. Interrill detachment is described as a rate proportional to the square of the rainfall intensity, and is computed as a function of precipitation, canopy interception, ground cover, and the spatial distribution of rills on the slope.

KINEROS- A Kinematic Runoff and Erosion Model

KINEROS (Woolhiser, Smith, and Goodrich, 1989) is a physically-based, event oriented model developed by the U.S. Dept. of Agriculture, Agricultural Research Service in Tucson, Arizona in 1987. An updated version of KINEROS is currently being developed by a European group. Designed for small watersheds, KINEROS contains 42 subroutines simulating rainfall interception, infiltration, surface runoff, erosion and sediment transport. Numerical solution of the partial differential equations of continuity and mass balance used in KINEROS are derived through finite difference methods. Watershed surface and channel networks are represented in the model through rectangular planes and channels which are arranged in a way to allow for the accounting of spatial variability of rainfall, infiltration, runoff, and erosion parameters. KINEROS has the capability to allow a plurality of these rectangular plane surface elements to be grouped side by side in a series within a watershed. The KINEROS model does not maintain a hydrologic water balance between storm events, and thus was designed primarily for single event simulations.

Watershed runoff is modeled through the use of subroutines which account for interception, infiltration, overland flow, and channel routing. Modeling of the infiltration process begins when the calculated "interception depth" value is exceeded by net rainfall. Two parameters are key to the infiltration model; the effective hydraulic conductivity, and a "net capillary drive" value which relates the unsaturated conductivity of the soil to relative volumetric soil water content and the soil matrix potential. When the rate of rainfall exceeds the infiltration rate, Hortonian overland flow is modeled as a one-dimensional flow process in conjunction with the continuity equation. Channel routing is represented by the kinematic approximations to the equations of unsteady, gradually varied flow. In addition to surface and channel elements, a watershed may contain up to three reservoir elements. Inflow to each reservoir can come from one or two channels. Outflow is calculated as a function of depth and produced through an uncontrolled outlet structure. Precipitation on the reservoir surface and infiltration through the reservoir bed are not considered.

The modeling of erosion processes by KINEROS is partitioned into two areas of concentration: upland erosion and channel erosion. The quantification of sediment transport parameters in both regions is solved using partial differential equations of mass balance similar to that for kinematic wave approximation of the St. Venant equations for water flow. The modeling of upland erosion consists of two groups of subroutines representing raindrop erosion and surface water erosion, respectively. Input values for quantifying rainfall splash erosion include: rainfall rate, lateral flow, raindrop diameter, depth of runoff, and a soil erodibility factor related to the K value from the Universal Soil Loss Equation. Splash

erosion uses a reduction factor, which decreases as depth of runoff increases. Surface water erosion is modeled as a kinetic transfer process with variable inputs of: 1) the sediment concentration at the equilibrium transport capacity, 2) the current local sediment concentrations, and 3) the transfer rate coefficient. KINEROS supplies a choice of 6 sediment transport capacity relationships depending on the physical variabilities of watershed parameters. These six relationships are: The Simple Tractive Force Equation (Meyer and Wischmeier 1969), The Unit Stream Power Relationships (Yang 1972), The Bagnold/Kilinc Equation (Kilinc and Richardson 1973), The Ackers and White Relationships (Ackers and White 1973), The Yalin Relationships (Yalin 1963), and The Engelund and Hansen Equation (Engelund and Hansen 1967). The initial value of sediment concentration at ponding is related to splash erosion, rainfall rate, initial lateral inflow, and particle settling velocity. Local sediment concentration values are solved through a four-point implicit finite-difference scheme as sediment concentration values are tracked through the watershed. The transfer rate coefficient represents erodibility when transport capacity exceeds sediment concentration, and deposition when sediment concentration exceeds transport capacity. The transfer rate coefficient for erodibility is related to the soil erodibility factor (K) from the Universal Soil Loss Equation, and the fractional clay content. The transfer rate coefficient for deposition is related to the particle fall velocity, water depth, and the ratio between transport capacity and sediment concentration.

Because the general approach to sediment transport simulation for channels is nearly identical for upland areas, the mass balance equation used in the KINEROS erosion model is also applicable to channel and distributed surface flow. The major differences are the deletion of splash erosion and the increased importance of sediment inflow values. Sediment particle size distribution is entered by the user for the modeling of downstream deposition rates. Sediment concentration in a channel is computed for each node, starting at the first node below the upstream channel boundary, and routed downstream.

KINEROS is run interactively, with the program prompting the user for names of input and output files. KINEROS reads data from three input files. One file contains rainfall data for all the rain gages in or near the watershed. The second file contains the hydrologic features of the network of planes and channels which describe the watershed. These include: size, shape, and location of elements, hydraulic roughness parameters, infiltration parameters, and erosion parameters. The third file contains data describing hydrologic features of any ponds that are part of the watershed. The KINEROS input files have been constructed with each input variable designation appearing above the space where the value should be entered.

KYERMO- The Kentucky Erosion Model

KYERMO (The Kentucky Erosion Model) is a single event land surface erosion model that can be used to predict sheet and rill erosion. KYERMO was originally developed as a research tool at the University of Kentucky by Michael C. Hirschi and Billy J. Barfield. The model takes a physically-based

approach in its analysis of the hydrologic cycle. KYERMO models the following processes: precipitation, infiltration, runoff, sheet erosion, rill erosion and development, channel flow routing, and sediment routing.

The runoff generation component of KYERMO consists of precipitation analyses, surface water ponding, infiltration, and overland flow routing. KYERMO keeps track of surface water ponding with an empirical relationship for potential surface water storage. The equation predicts ponding as a function of the land surface roughness and surface slope. Infiltration is modeled with an extension of the Green-Ampt-Mein-Larson model developed by Moore (1981). The Kinematic Wave equations are used to model overland flow as well as channel flow. The dimensions of the rills change dynamically in response to deposition and erosion. Hydraulic information for each cross section is updated at the end of each time step.

KYERMO is capable of modeling the processes of sediment detachment caused by raindrops, rill flow sediment detachment, and rill wall sloughing. Sediment detachment due to raindrop impact is calculated using the composite equation of Bubenzer and Jones (1971) with a slope term added by Quansah (1981). Rill sediment detachment is calculated with an equation developed by Foster (1982), which is based on bed shear. Rill detachment is calculated on a subsection basis for each cross section. After erosion is calculated in each subsection, the actual cross section modification is based on a weighting of the individual subsection detachment depths. The final calculation in the sediment generation routine is to determine if the rill banks will slough. This is accomplished with a method proposed by Massad and Wu (1984).

In the sediment routing component of KYERMO, transport and deposition of sediment is calculated for both sheet and rill flow. Two transport functions are available for either sheet or rill flow. The first equation is a modified Yalin (1963) equation developed by Foster and Meyer (1972). The second equation is a modification of Yang's equation (1973). The modification of Yang's equation involves distributing the sediment transport among particle sizes. This is accomplished by first calculating the transport for a D_{50} particle size and then distributing the sediment among the various sizes according to their relative transport capacity. Sheet flow transport, for the material detached by rainfall, is modeled by first calculating the potential transport rate of the overland flow. If the amount of material detached is greater than the transport rate, then the remaining material is re-deposited and must be re-detached at a later time step. If the detached material is less than the transport capacity, all of the detached material is transported. The same calculations are made for rill flow as in sheet flow, except the rills have more sources of sediment. Potential sediment load in rills is the summation of shear detachment of bed material, upstream sediment inflow, sediment delivery from lateral sheet flow, and rill bank sloughing. Sediment transport capacity is calculated for the rill, then either deposition or erosion processes are performed.

IV. CONCLUSION

Continuing research on the physics of rill and interrill sediment discharge has greatly augmented the understanding of watershed erosive processes. However, the application of physically-based models to large watersheds, for which sufficient sediment yield and runoff data are often unavailable, is not a common practice. Furthermore, the physically-based models contain equations with constants and exponents which must be determined for each watershed, and the subdivision of a large watershed into rill and interrill areas would require an enormous amount of time and effort. In contrast, empirical models require information on topography, soils, precipitation, and land use which can be estimated from maps and simple field surveys. In modeling decisions, care must be taken that the level of detail of the erosion processes represented by the numerical model and field data is commensurate with the objectives of the application. A summary of the models reviewed is provided in Table 1.

Table 1
Comparison of Land Surface Erosion Models

	SP	AGNPS	RUNOFF	WEPP	KINEROS	KYERMO
Proprietary	No	No	No	No	No	No
User's Manual available	Yes	Yes	Yes	Yes	Yes	--
Computer needs	PC	PC	PC	PC	PC	PC
Current version number	--	3.65	3.0	91.5	--	--
Most recent update	3/89	6/92	6/92	9/91	5/89	7/87
Single event yield analysis	Yes	Yes	Yes	Yes	Yes	Yes
Average annual yield analysis	No	No	No	Yes	No	No
Division of watershed into subbasins	No	Yes	Yes	Yes	Yes	Yes
Raindrop impact detachment	No	No	Yes	Yes	Yes	Yes
Rill and interrill erosion processes considered separately	No	No	No	Yes	Yes	Yes
Rill formation processes modeled	No	No	No	No	Yes	Yes
Channel transport/deposition	No	Yes	Yes	No	No	No

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Appendix B

Glossary

ACCURACY Degree of conformity of a measure to a standard or true value.

ACTIVE BED The active bed is the layer of material between the bed surface and a hypothetical depth at which no transport will occur for the given gradation of bed material and flow conditions. See also, ACTIVE LAYER.

ACTIVE LAYER The depth of material from bed surface to equilibrium depth continually mixed by the flow, but it can have a surface of slow moving particles that shield the finer particles from being entrained by the flow. See Figure B-1.

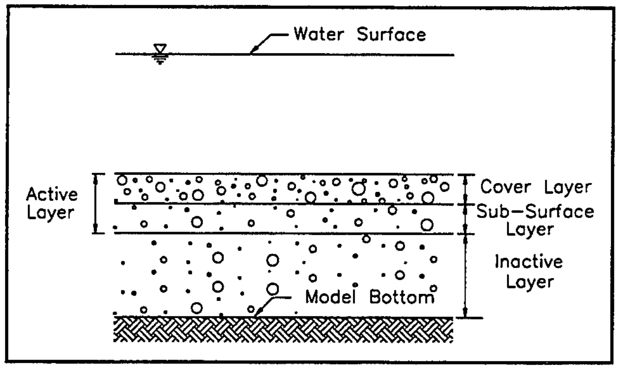

Figure B-1
Composition of the Active Layer

AGGRADATION The geologic process by which stream beds, floodplains, and the bottoms of other water bodies are raised in elevation by the deposition of material eroded and transported from other areas. It is the opposite of degradation.

ALGORITHM A procedure for solving a mathematical problem in a finite number of steps that frequently involves repetition of an operation. A step by step procedure for solving a problem or accomplishing an end. A set of numerical steps or routines to obtain a numerical output from a numerical input.

ALLUVIAL Pertains to alluvium deposited by a stream or flowing water.

ALLUVIAL DEPOSIT Clay, silt, sand, gravel, or other sediment deposited by the action of running or receding water.

ALLUVIAL REACH A reach of river with a sediment bed composed of the same type of sediment material as that moving in the stream.

ALLUVIAL STREAM A stream whose channel boundary is composed of appreciable quantities of the sediments transported by the flow, and which generally changes its bed forms as the rate of flow changes.

ALLUVIUM A general term for all detrital deposits resulting directly or indirectly from the sediment transported by (modern) streams, thus including the sediments laid down in riverbeds, floodplains, lakes, fans, and estuaries.

ARMOR LAYER See ARMORING.

ARMORING The process of progressive coarsening of the bed layer by removal of fine particles until it becomes resistant to scour. The coarse layer that remains on the surface is termed the "armor layer". Armoring is a temporary condition; higher flows may destroy an armor layer and it may re-form as flows decrease. Or simply, the formation of a resistant layer of relatively large particles resulting from removal of finer particles by erosion.

AVERAGE END CONCEPT The averaging of the two end cross sections of a reach in order to smooth the numerical results.

BACKWATER PROFILE Longitudinal profile of the water surface in a stream where the water surface is raised above its normal level by a natural or artificial obstruction.

BANK SEDIMENT RESERVOIR The portion of the alluvium on the sides of a channel. See Figure B-2. (Note: HEC-6 only uses the BED SEDIMENT RESERVOIR as the source-sink of material.)

BED FORMS Irregularities found on the bottom (bed) of a stream that are related to flow characteristics. They are given names such as "dunes," "ripples," and "antidunes." They are related to the transport of sediment and interact with the flow because they change the roughness of the stream bed. An analog to stream bed forms are desert sand dunes (although the physical mechanisms for their creation and movement may be different).

BED LAYER An arbitrary term used in various procedures for computation of sediment transport. From observation of slow motion movies of laboratory flume experiments, H. Einstein defined the "bed layer" as: "A flow layer, 2 grain diameters thick, immediately above the bed. The thickness of the bed layer varies with the particle size."

BED LOAD Material moving on or near the stream bed by rolling, sliding, and sometimes making brief excursions into the flow a few diameters above the bed, i.e. jumping. The term "saltation" is sometimes used in place of "jumping." Bed load is bed material that moves in continuous contact with the bed; contrast with SUSPENDED LOAD.

BED LOAD DISCHARGE The quantity of bed load passing a cross section in a unit of time, i.e. the rate. Usually presented in units of tons per day. May be measured or computed. See BED LOAD.

BED MATERIAL The sediment mixture of which the moving bed is composed. In alluvial streams, bed material particles are likely to be moved at any moment or during some future flow condition. Bed material consists of both bed load and suspended load. Contrast with WASH LOAD.

BED MATERIAL DISCHARGE The total rate (tons/day) at which bed material (see BED MATERIAL) is transported by a given flow at a given location on a stream.

BED MATERIAL LOAD The total rate (tons/day) at which bed material is transported by a given location on a stream. It consists of bed material moving both as bed load and suspended load. Contrast with WASH LOAD.

BEDROCK A general term for the rock, usually solid, that underlies soil or other unconsolidated, bed material.

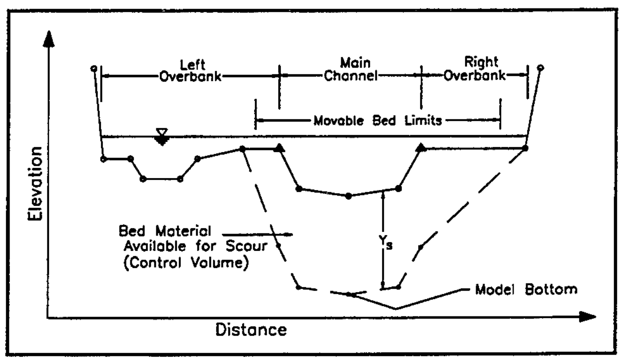

Figure B-2
Sediment Material in the Streambed

BED SEDIMENT CONTROL VOLUME The source-sink component of sediment sources in a river system (the other component is the suspended sedment in the inflowing discharge). Its user-defined dimensions are the movable bed width and depth, and the average reach length.

BOUNDARY CONDITIONS Definition or statement of conditions or phenomena at the boundaries. Water surface elevations, flows, sediment concentrations, etc., that are specified at the boundaries of the area being modeled. The downstream water surface elevation and the incoming upstream water and sediment discharges are the standard HEC-6 boundary conditions.

BOUNDARY ROUGHNESS The roughness of the bed and banks of a stream or river. The greater the roughness, the greater the frictional resistance to flows; and, hence, the greater the water surface elevation for any given discharge.

BRAIDED CHANNEL A stream that is characterized by random interconnected channels divided by islands or bars. Bars which divide the stream into separate channels at low flows are often submerged at high flow.

CHANNEL A natural or artificial waterway which periodically or continuously contains moving water.

CHANNEL INVERT The lowest point in the channel.

CHANNEL STABILIZATION A stable channel is neither progressively aggrading nor degrading, or changing its cross-sectional area through time. It could aggrade or degrade slightly, but over the period of a year, the channel would remain similar in shape and dimensions and position to previous times. Unstable channels are depositing or eroding in response to some exterior conditions. Stabilization techniques consist of bank protection and other measures that work to transform an unstable channel into a stable one.

CLAY See Table B-1.

COBBLES See Table B-1.

Table B-1[1]
Scale for Size Classification of Sediment Particles

Class Name	Millimeters	Feet	PHI Value
Boulders	> 256	--	< -8
Cobbles	256 - 64	--	-8 to -6
Very Coarse Gravel	64 - 32	.148596	-6 to -5
Coarse Gravel	32 - 16	.074216	-5 to -4
Medium Gravel	16 - 8	.037120	-4 to -3
Fine Gravel	8 - 4	.018560	-3 to -2
Very Fine Gravel	4 - 2	.009279	-2 to -1
Very Coarse Sand	2.0 - 1.0	.004639	-1 to 0
Coarse Sand	1.0 - 0.50	.002319	0 to +1
Medium Sand	0.50 - 0.25	.001160	+1 to +2
Fine Sand	0.25 - 0.125	.000580	+2 to +3
Very Fine Sand	0.125 - 0.0625	.000288	+3 to +4
Coarse Silt	0.0625 - 0.031	.000144	+4 to +5
Medium Silt	0.031 - 0.016	.000072	+5 to +6
Fine Silt	0.016 - 0.008	.000036	+6 to +7
Very Fine Silt	0.008 - 0.004	.000018	+7 to +8
Coarse Clay	0.004 - 0.0020	.000009	+8 to +9
Medium Clay	0.0020 - 0.0010	--	+9 to +10
Fine Clay	0.0010 - 0.0005	--	+10 to +11
Very Fine Clay	0.005 - 0.00024	--	+11 to +12
Colloids	<0.00024	--	> +12

[1] Portions of Table B-1 are taken from EM 1110-2-4000, March 1989.

COHESIVE SEDIMENTS Sediments whose resistance to initial movement or erosion is affected mostly by cohesive bonds between particles.

COMPUTATIONAL HYDROGRAPH A sequence of discrete steady flows, each having a specified duration in days, is used to represent the continuous discharge hydrograph. This is done to minimize the number of time steps needed to simulate a given time period, and, thus minimize computer time. See Figure B-3.

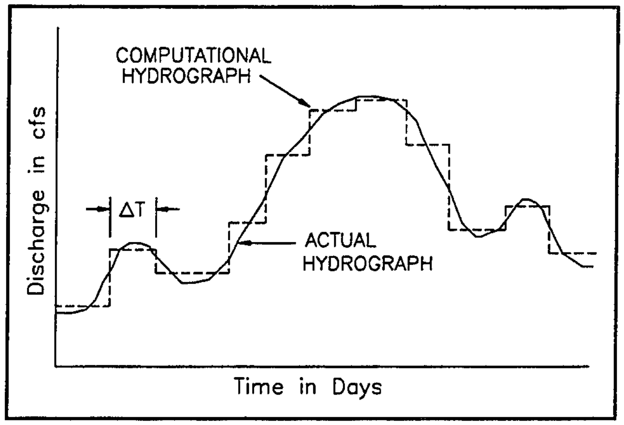

Figure B-3
Computational Hydrograph

CONCENTRATION OF SEDIMENT The dry weight of sediment per unit volume of water-sediment mixture, i.e., mg/ℓ. (Note: In earlier writings, concentration was calculated as the ratio of the dry weight of sediment in a water-sediment mixture to the total weight of the mixture multiplied by 1,000,000. It was expressed as parts per million, i.e., ppm. Either method gives the same result, within one percent, for concentrations up to 16,000 mg/ℓ. A correction is needed for concentrations in excess of that value.) The conversion to mg/ℓ (miligrams per liter) from ppm (parts per million) is as follows:

$$\text{mg}/\ell = K \cdot (\text{ppm}) = K \cdot \frac{\text{weight of sediment} \cdot 1{,}000{,}000}{\text{weight of water - sediment mixture}}$$

where: K = correction factor

CONCEPTUAL MODEL A simplification of prototype behavior used to demonstrate concepts.

CONSOLIDATION The compaction of deposited sediments caused by grain reorientation and by the squeezing out of water trapped in the pores.

CONTROL POINT The downstream boundary of the main river segment and the junction point of each tributary. In Figure B-4, each control point is designated by a circled number.

CONVERGENCE The state of tending to a unique solution. A given scheme is convergent if an increasingly finer computational grid leads to a more accurate solution.

CONVEYANCE A measure of the carrying capacity of the channel section. Flow is directly proportional to conveyance for steady flow. From Manning's equation, the proportionality factor is the square root of the energy slope.

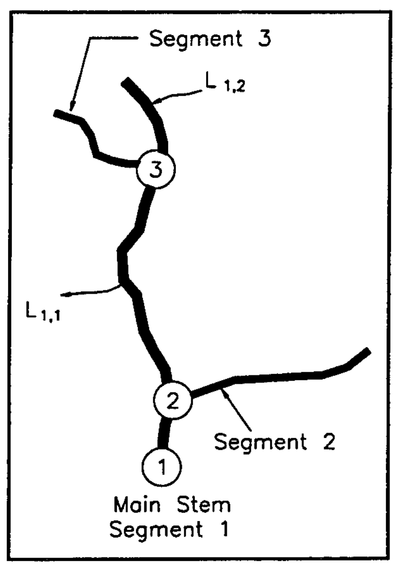

Figure B-4
Control Point Numbering

COVER LAYER One of the two sublayers of the active layer. It lies above the sub-surface layer (the second sublayer in the active layer). See Figure B-1.

CRITICAL BED SHEAR STRESS See CRITICAL TRACTIVE FORCE.

CRITICAL DEPTH If discharge is held constant and the water depth allowed to decrease, as in the case of water approaching a free overfall, velocity head will increase, pressure head will decrease, and total energy will decrease toward a minimum value where the rate of decrease in the pressure head is just counter-balanced by the rate of increase in velocity head. This is the critical depth. More generally, the critical depth is the depth of flow that would produce the minimum total energy head.

CRITICAL FLOW The state of flow where the water depth is at the critical depth and when the inertial and gravitational forces are equal.

CRITICAL TRACTIVE FORCE The critical tractive force is the maximum unit tractive force that will not cause serious erosion of the material forming the channel bed on a level surface.

CROSS SECTION Depicts the shape of the channel in which a stream flows. Measured by surveying the stream bed elevation across the stream on a line perpendicular to the flow. Necessary data for the computation of hydraulic and sediment transport information.

CROSS-SECTIONAL AREA The area of a cross section between the stream bed and the water surface.

DEGRADATION The geologic process by which stream beds, floodplains, and the bottoms of other water bodies are lowered in elevation by the removal of material from the boundary. It is the opposite of aggradation.

DEPOSITION The mechanical or chemical processes through which sediments accumulate in a (temporary) resting place. The raising of the stream bed by settlement of moving sediment that may be due to local changes in the flow, or during a single flood event.

DEPTH OF FLOW The depth of flow is the vertical distance from the bed of a stream to the water surface.

DISCHARGE The discharge (Q) is the volume of a fluid or solid passing a cross section of a stream per unit time.

DISTRIBUTARIES Diverging streams which do not return to the main stream, but discharge into another stream or the ocean.

DOMINANT DISCHARGE A particular magnitude of flow which is sometimes referred to as the "channel forming" discharge. Empirical relations have been developed between "equilibrium" stream width, depth, and slope and dominant discharge. It has been variously defined as the bank full flow, mean annual discharge, etc.

DRAFT DEPTH The depth measured perpendicularly from the water surface to the bottom of a boat, ship, etc. (i.e., a "clearance" depth).

DROP A structure in an open conduit or canal installed for the purpose of dropping the water to a lower level and dissipating its energy. It may be vertical or inclined; in the latter case it is usually called a chute.

EFFECTIVE (GRAIN) SIZE The diameter of the particles in an assumed rock or soil that would transmit water at the same rate as the rock or soil under consideration, and that is composed of spherical particles of equal size and arranged in a specific manner. The effective grain size is that single particle diameter that best depicts the bed material properties. The D50 grain size is often used as the effective grain size.

EQUILIBRIUM DEPTH The minimum water depth for the condition of no sediment transport.

ENTRAINMENT The carrying away of bed material produced by erosive action of moving water.

EQUILIBRIUM LOAD The amount of sediment that a system can carry for a given discharge without an overall accumulation (deposit) or scour (degradation).

EROSION The wearing away of the land surface by detachment and movement of soil and rock fragments through the action of moving water and other geological agents.

FALL VELOCITY The falling or settling rate of a particle in a given medium.

FIXED BED MODEL Model in which the bed and side materials are nonerodible. Deposition does not occur as well.

FLOW DURATION CURVE A measure of the range and variability of a stream's flow. The flow duration curve represents the percent of time during which specified flow rates are exceeded at a given location. This is usually presented as a graph of flow rate (discharge) versus percent of time that flows are greater than, or equal to, that flow.

FREQUENCY The number of repetitions of a periodic process in a certain time period.

GEOLOGIC CONTROL A local rock formation or clay layer that limits (within the engineering time frame) the vertical and/or lateral movement of a stream at a particular point. Note that man-made controls such as drop structures also exist.

GRADATION The proportion of material of each particle size, or the frequency distribution of various sizes, constituting a particulate materialsuch as a soil, sediment, or sedimentary rock. The limits of each size are chosen arbitrarily. Four different gradations are significant: the gradation of the suspended load, the gradation of the bed load, the gradation of the material comprising the bed surface, and the gradation of material beneath the bed surface.

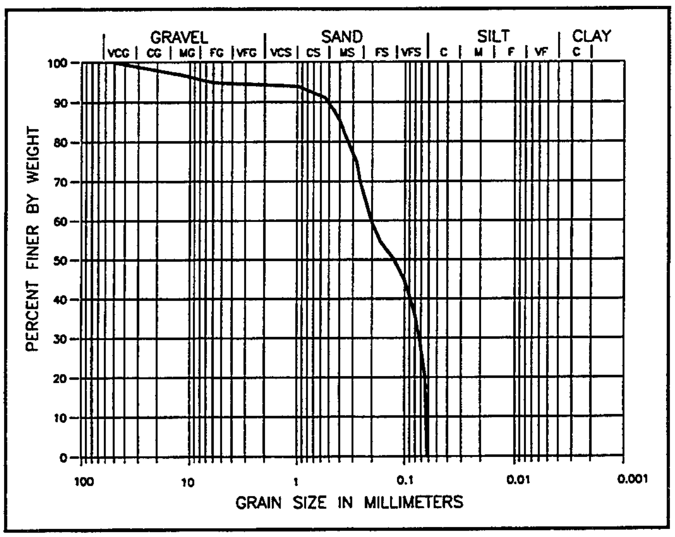

Figure B-5
Sample Gradation Curve

GRADATION CURVE Sediment samples usually contain a range of grain sizes, and it is customary to break this range into classes of percentages of the total sample weight contained in each class. After the individual percentages are accumulated, a graph, the "gradation curve," shows the grain size versus the accumulated percent of material that is finer than that grain size. These curves are used by movable boundary models to depict the bed sediment material properties (e.g., grain size distribution of the bed material). See Figure B-5.

GRAIN SHAPE FACTOR See PARTICLE SHAPE FACTOR.

GRAIN SIZE See PARTICLE SIZE.

GRAIN SIZE DISTRIBUTION (GRADATION) A measure of the variation in grain (particle) sizes within a mixture. Usually presented as a graph of grain diameter versus percent of the mixture that is finer than that diameter. See Figure B-5.

GRAVEL See Table B-1.

HISTORIC FLOWS The collection of recorded flow data for a stream during the period of time in which steam gages were in operation.

HYDRAULIC MODEL A physical scale model of a river used for engineering studies.

HYDRAULICS The study and computation of the characteristics, e.g. depth (water surface elevation), velocity and slope, of water flowing in a stream or river.

HYDROGRAPH A graph showing, for a given point on a stream or conduit, the discharge,water surface elevation, stage, velocity, available power, or other property of water with respect to time.

HYDROLOGY The study of the properties, distribution, and circulation of water on the surface of the land, in the soil, and in the atmosphere.

INACTIVE LAYER The depth of material beneath the active layer. See Figure B-1.

INCIPIENT MOTION The flow condition at which a given size bed particle just begins to move. Usually related to a "threshold" shear stress.

INEFFECTIVE FLOW When high ground or some other obstruction such as a levee prevents water from flowing into a subsection, the area up to that point is ineffective for conveying flow and is not used for hydraulic computations until the water surface exceeds the top elevation of the obstruction. The barrier can be a natural levee, man-made levee or some other structure.

INFLOWING LOAD CURVE See SEDIMENT RATING CURVE.

INITIAL CONDITIONS The value of water levels, velocities, concentrations, etc., that are specified everywhere in the mesh at the beginning of a model run. For an iterative solution, the initial conditions represent the first estimate of the variables the model is trying to solve.

IN SITU In (its original) place.

LEFT OVERBANK See OVERBANK.

LOCAL INFLOW/OUTFLOW POINT Points along any river segment at which water and sediment enter or exit that segment as a local flow. Each local inflow/outflow point is designated by an arrow and $L_{n,m}$ where *n* is the segment number and m is the sequence number (going upstream) of the local inflow/outflow points located along segment n, as shown in Figure B-6.

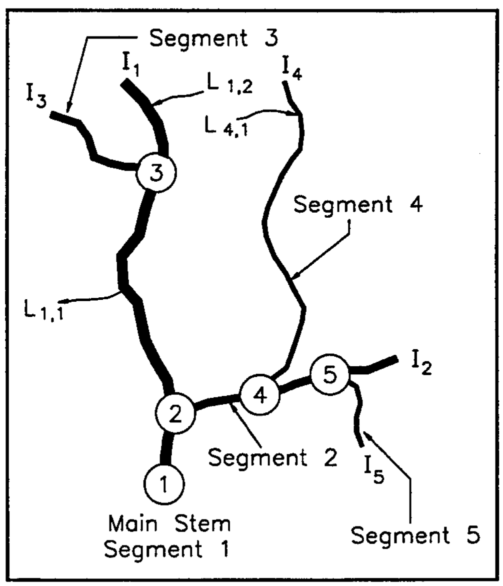

Figure B-6
Local Inflow/Outflow Points

LOCAL SCOUR Erosion caused by an abrupt change in flow direction or velocity. Examples include erosion around bridge piers, downstream of stilling basins, at the ends of dikes, and near snags.

M1 AND M2 CURVES M1 and M2 curves represent mild sloping water surface profiles.

MAIN STEM The primary river segment with its outflow at the downstream end of the model.

MANNING'S EQUATION The empirical Manning's equation commonly applied in water surface profile calculations defines the relationship between surface roughness, discharge, flow geometry, and rate of friction loss for a given stream location.

MANNING'S *n* VALUE *n* is the coefficient of roughness with the dimensions of $T \cdot L^{-1/3}$. *n* accounts for energy loss due to the friction between the bed and the water. In fluvial hydraulics (movable boundary hydraulics), the Manning's *n* value includes the effects of all losses, such as grain roughness of the movable bed, form roughness of the movable bed, bank irregularities, vegetation, bend losses, and junction losses. Contraction and expansion losses are not included in Manning's *n*, but are typically accounted for separately.

MATHEMATICAL MODEL A model that uses mathematical expressions (i.e., a set of equations, usually based upon fundamental physical principles) to represent a physical process.

MEANDERING STREAM An alluvial stream characterized in planform by a series of pronounced alternating bends. The shape and existence of the bends in a meandering stream are a result of alluvial processes and not determined by the nature of the terrain (geology) through which the stream flows.

MODEL A representation of a physical process or thing that can be used to predict the process's or thing's behavior or state.

Examples: A conceptual model: If I throw a rock harder, it will go faster.
A mathematical model: $F = m \cdot a$
A hydraulic model: Columbia River physical model.

MOVABLE BED That portion of a river channel cross section that is considered to be subject to erosion or deposition.

MOVABLE BED LIMITS The lateral limits of the movable bed that define where scour or deposition occur. See Figure B-2.

MOVABLE BED MODEL Model in which the bed and/or side material is erodible and transported in a manner similar to the prototype.

NETWORK MODEL A network model is a network of main stem, tributary, and local inflow/outflow points that can be simulated simultaneously and in which tributary sediment transport can be calculated.

NORMAL DEPTH The depth that would exist if the flow were uniform is called normal depth.

NUMERICAL EXPERIMENTS Varying the input data, or internal parameters, of a numerical model to ascertain the impact on the output.

NUMERICAL MODEL A numerical model is the representation of a mathematical model as a sequence of instructions (program) for a computer. Given approximate data, the execution of this sequence of instructions yields an approximate solution to the set of equations that comprise the mathematical model.

ONE-DIMENSIONAL ENERGY EQUATION This equation has the same form as the Bernoulli Equation and the same terms are present. In addition, an α term has been added to correct for velocity distribution.

OPERATING POLICY See OPERATING RULE.

OPERATING RULE The rule that specifies how water is managed throughout a water resource system. Often they are defined to include target system states, such as storage, above which one course of action is implemented and below which another course is taken.

OVERBANK In a river reach, the surface area between the bank on the main channel and the limits of the floodplain. See Figure B-7.

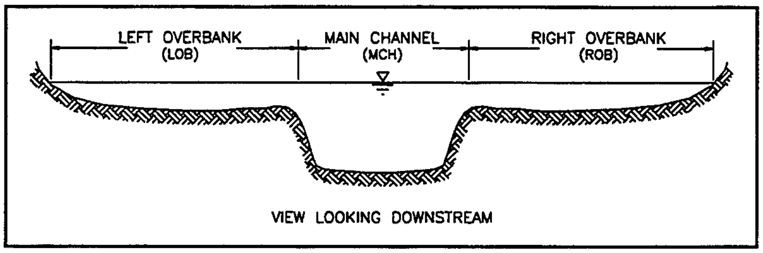

Figure B-7
Examples of Overbanks

OVERDREDGING The additional depth dredged beyond the minimum dredging depth used to provide sufficient navigational depth, to minimize redredging, and to help compensate for the sloughing off and resettling of sediment after dredging occurs

PARAMETER Any set of physical properties whose values determine the characteristics or behavior of something.

PARTICLE SHAPE FACTOR The particle shape factor of a perfect sphere is 1.0 and can be as low as 0.1 for very irregular shapes. It is defined by:

$$SF = \frac{c}{(a \cdot b)^{1/2}}$$

where: a,b,c = the lengths of the longest, intermediate, and shortest, respectively, mutually perpendicular axes on a sediment particle.

PARTICLE SIZE A linear dimension, usually designated as "diameter," used to characterize the size of a particle. The dimension may be determined by any of several different techniques, including sedimentation sieving, micrometric measurement, or direct measurement.

PERMEABILITY The property of a soil that permits the passage of water under a gradient of force.

PLANFORM The shape and size of channel and overbank features as viewed from directly above.

PRIMARY TRIBUTARY A tributary that is directly connected to or that joins with the main river segment.

PROTOTYPE The full-sized structure, system process, or phenomenon being modeled.

QUALITATIVE Relating to or involving quality or kind.

RATING CURVE See STAGE-DISCHARGE CURVE.

REACH (1) The length of a channel, uniform with respect to discharge, depth, area, and slope, e.g., "study reach," "typical channel reach" or "degrading reach," etc. (2) The length of a stream between two specified gaging stations.

RIGHT OVERBANK See OVERBANK.

RIPPLES Small triangular-shaped bed forms, similar to dunes but have much smaller heights and are 0.3m or less in length. They develop when the Froude number is less than 0.3.

RIVER SEGMENT See STREAM SEGMENT.

S1 AND S2 CURVES S1 and S2 curves represent steep sloping water surface profiles.

SAND See Table B-1.

SATURATION The degree to which voids in soil are filled with water.

SCOUR The enlargement of a flow section by the removal of bed material through the action of moving water.

SECONDARY CURRENTS (OR FLOW) The movement of water particles on a cross section normal to the longitudinal direction of the channel.

SEDIMENT (1) Particles derived from rocks or biological materials that have been transported by a fluid. (2) Solid material (sludges) suspended in or settled from water. A collective term meaning an accumulation of soil, rock and mineral particles transported or deposited by flowing water.

SEDIMENTATION A broad term that pertains to the five fundamental process responsible for the formation of sedimentary rocks: (1) weathering, (2) detachment, (3) transportation, (4) deposition (sedimentation), and (5) diagenesis; and to the gravitational settling of suspended particles that are heavier than water.

SEDIMENTATION DIAMETER The diameter of a sphere of the same specific weight and the same terminal settling velocity as the given particle in the same fluid.

SEDIMENT DISCHARGE The mass or volume of sediment (usually mass) passing a stream cross section in a unit of time. The term may be qualified, for example; as suspended-sediment discharge, bed load discharge, or total-sediment discharge. See SEDIMENT LOAD.

SEDIMENT-DISCHARGE RELATIONSHIP Tables which relate inflowing sediment loads to water discharge for the upstream ends of the main stem, tributaries, and local inflows.

SEDIMENT LOAD A general term that refers to material in suspension and/or in transport. It is not synonymous with either discharge or concentration. It may also refer to a particular type of load; e.g. total, suspended, wash, bed, or material.

SEDIMENT PARTICLE Fragments of mineral or organic material in either a singular or aggregate state.

SEDIMENT TRANSPORT (RATE) See SEDIMENT DISCHARGE.

SEDIMENT TRANSPORT FUNCTION A formula or algorithm for calculating the sediment transport rate given the hydraulics and bed material at a cross section. Most sediment transport functions compute the bed material load capacity. The actual transport may be less than the computed capacity due to armoring, geologic controls, etc.

SEDIMENT TRANSPORT ROUTING The computation of sediment movement for a selected length of stream (reach) for a period of time with varying flows. Application of sediment continuity relations allow the computation of aggradation and deposition as functions of time.

SEDIMENT TRAP EFFICIENCY See TRAP EFFICIENCY.

SETTLING VELOCITY See FALL VELOCITY.

SHAPE FACTOR See PARTICLE SHAPE FACTOR.

SHEAR INTENSITY A dimensionless number that is taken from Einstein's bed load function. It is the inverse of Shield's parameter.

SHEAR STRESS Frictional force per unit of bed area exerted on the bed by the flowing water. An important factor in the movement of bed material.

SHIELD'S DETERMINISTIC CURVE A curve of the dimensionless tractive force plotted against the grain Reynolds number (i.e., $U_Q \cdot D_s/v$ where, U_Q = turbulent shear velocity, D_s = characteristic or effective size of the grains or roughness elements, v = kinematic viscosity) and which is used to help determine the CRITICAL TRACTIVE FORCE.

SHIELD'S PARAMETER A dimensionless number referred to as a dimensionless shear stress. The beginning of motion of bed material is a function of this dimensionless number.

$$\frac{\tau_c}{(\gamma_s - \gamma)\, D_s}$$

where: τ_c = critical tractive force
γ_s = specific weight of the particle
γ = specific weight of water
D_s = characteristic or effective size of the grains or roughness elements

SIEVE DIAMETER The smallest standard sieve opening size through which a given particle of sediment will pass.

SILT See Table B-1.

SILTATION An unacceptable term. Use sediment deposition, sediment discharge, or sediment yield as appropriate.

SIMULATE To express a physical system in mathematical terms.

SINUOSITY A measure of meander "intensity." Computed as the ratio of the length of a stream measured along its thalweg (or centerline) to the length of the valley through which the stream flows.

SORTING The dynamic process by which sedimentary particles having some particular characteristic (such as similarity of size, shape, or specific gravity) are naturally selected and separated from associated but dissimilar particles by the agents of transportation. Also, see GRADATION.

SPLIT FLOW Flow that leaves the main river flow and takes a completely different path from the main river [Case (a)]. Split flow can also occur in the case of flow bifurcation around an island [Case (b)]. See Figure B-8.

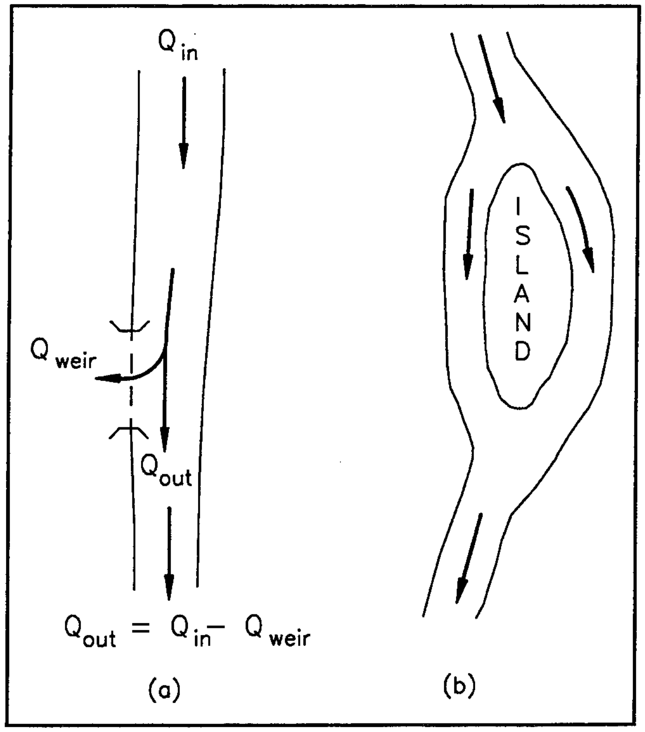

Figure B-8
Split Flow

STABLE CHANNEL A stream channel that does not change in planform or bed profile during a particular period of time. For purposes of this glossary the time period is years to tens of years.

STAGE-DISCHARGE (RATING) CURVE Defines a relationship between discharge and water surface elevation at a given location.

STANDARD STEP METHOD Method where the total distance is divided into reaches by cross sections at fixed locations along the channel and, starting from one control, profile calculations proceed in steps from cross section to cross section to the next control.

STEADY STATE MODEL Model in which the variables being investigated do not change with time.

STREAM GAGE A device that measures and records flow characteristics such as water discharge and water surface elevation at a specific location on a stream. Sediment transport measurements are usually made at stream gage sites.

STREAM POWER The product of bed shear stress and mean cross-sectional velocity at a cross section for a given flow.

STREAM PROFILE A plot of the elevation of a stream bed versus distance along the stream.

STREAM SEGMENT A stream segment is a specified portion of a river with an upstream inflow point and with a downstream termination at a control point. Primary Inflow points are designated by I_n, where *n* is the segment number. Primary inflow points are always at the upstream most end of a tributary or main stem segment. See Figure 3-7.

SUBCRITICAL FLOW The state of flow where the water depth is above the critical depth. Here, the influence of gravity forces dominate the influences of inertial forces, and flow, having a low velocity, is often described as tranquil.

SUB-SURFACE LAYER The sub-surface layer is composed of well mixed sediments brought up from the inactive layer plus sediment which has deposited from the water column. It will replenish the cover layer and thereby supply bed sediment as required to meet sediment transport capacity. When the weight in the sub-surface layer becomes less than the weight required to cover 100% of the bed surface to a depth of two times the size of the largest particle in transport, a new sub-surface layer is brought up from the inactive layer. See Figure B-1.

SUPERCRITICAL FLOW The state of flow where the water depth is below the critical depth, inertial forces dominate the gravitational forces, and the flow is described as rapid or shooting.

SUSPENDED BED MATERIAL LOAD That portion of the suspended load that is composed of particle sizes found in the bed material.

SUSPENDED LOAD Includes both suspended bed material load and wash load. Sediment that moves in suspension is continuously supported in the water column by fluid turbulence. Contrast with BED LOAD.

SUSPENDED-SEDIMENT DISCHARGE The quantity of suspended sediment passing a cross section in a unit of time usually given in tons/day. See SUSPENDED LOAD.

TAIL WATER The water surface elevation downstream from a structure, such as below a dam, weir or drop structure.

THALWEG The line following the lowest part of a valley, whether under water or not. Usually the line following the deepest part or middle of the bed or channel of a river.

TOTAL SEDIMENT DISCHARGE The total rate at which sediment passes a given point on the stream (tons/day). See TOTAL SEDIMENT LOAD.

TOTAL-SEDIMENT LOAD (TOTAL LOAD) Includes bed load, suspended bed material load, and wash load. In general, total sediment load cannot be calculated or directly measured.

TRACTIVE FORCE When water flows in a channel, a force is developed that acts in the direction of flow on the channel bed. This force, which is simply the pull of water on the wetted area, is known as the tractive force. In a uniform flow, the equation for the unit tractive force (i.e., the average value to the tractive force per unit wetted area) is:

$$\tau_0 = \gamma RS$$

where: τ_0 = unit tractive force
γ = unit weight of water
R = the hydraulic radius
S = the slope of the channel

TRANSMISSIVE BOUNDARY A boundary (cross section) that will allow sediment that reaches it to pass without changing that cross section.

TRANSPORTATION (SEDIMENT) The complex processes of moving sediment particles from place to place. The principal transporting agents are flowing water and wind.

TRANSPORT CAPACITY The ability of the stream to transport a given volume or weight of sediment material of a specific size per time for a given flow condition. The units of transport capacity are usually given in Tons per day of sediment transported passed a given cross section for a given flow. Transport capacity for each sediment grain size is the transport potential for that size material multiplied by the actual fraction of each size class present in the bed and bank material.

TRANSPORT POTENTIAL Transport potential is the rate at which a stream could transport sediment of a given grain size for given hydraulic conditions if the bed and banks were composed entirely of material of that size.

TRAP EFFICIENCY Proportion of sediment inflow to a stream reach (or reservoir) that is retained within that reach (or reservoir). Computed as inflowing sediment volume minus outflowing sediment volume divided by inflowing sediment volume. Positive values indicate aggradation; negative values, degradation.

TRIBUTARY A river segment other than the main stem in which sediment transport is calculated. More generally, a stream or other body of water, surface or underground, that contributes its water to another and larger stream or body of water.

TURBULENCE In general terms, the irregular motion of a flowing fluid.

WASH LOAD That part of the suspended load that is finer than the bed material. Wash load is limited by supply rather than hydraulics. What grain sizes constitute wash load varies with flow and location in a stream. Sampling procedures that measure suspended load will include both wash load and suspended bed material load. Normally, that is of sediment particles smaller than 0.062 mm.

WATER COLUMN An imaginary vertical column of water used as a control volume for computational purposes. Usually the size of a unit area and as deep as the depth of water at that location in the river.

WATER DISCHARGE See STREAM DISCHARGE.

WATERSHED A topographically defined area drained by a river/stream or system of connecting rivers/streams such that all outflow is discharged through a single outlet. Also called a drainage area.

WEIR A small dam in a stream, designed to raise the water level or to divert its flow through a desired channel. A diversion dam.

WETTED PERIMETER The wetted perimeter is the length of the wetted contact between a stream of flowing water and its containing channel, measured in a direction normal to the flow.

Appendix C

Published Sources of Suspended and Bed Load Sediment Data for Large Drainage basins in California, Oregon and Washington (from Collins & Dunne, 1990)

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